AFIT/GAE/ENY/99M-01

A NONLINEAR PRE-FILTER TO PREVENT DEPARTURE AND/OR PILOT-INDUCED OSCILLATIONS (PIO) DUE TO ACTUATOR RATE LIMITING

THESIS

Michael J. Chapa, Captain, USAF

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Presented to the Faculty of the School of Engineering

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Air University

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

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Captain, USAF

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Preface

The purpose of this thesis was to develop an algorithm to prevent departure and/or pilot-induced oscillations (PIO) due to actuator rate limiting. Computer simulation, motion-based simulation, and finally, flight test were used to validate the thesis.

The study was conducted under the joint Air Force Institute of Technology (AFIT)/USAF Test Pilot School (TPS) program. I would like to thank my advisor, Dr. Liebst (AFIT), whose idea started the study (only to later find out we were not the first to investigate this concept). Mr. Eric Ohmit (Calspan Corp., Buffalo) helped me understand the nature of variable stability system (VSS) aircraft and the HAVE LIMITS TPS flight test program from Spring 97. Mr. Jeff Slutz of the Halifax Corporation (Wright-Patterson AFB) helped immensely with the Large Amplitude Multimode Aerospace Simulator (LAMARS) simulator testing. Also, Mr. Dave Leggett (Air Force Research Laboratory Air Vehicles Division) sponsored the project and provided assistance and suggestions.

I would especially like to thank the entire HAVE FILTER flight test team for making the flight test project a reality: Maj Kevin Ford (TPS staff monitor), LCDR LeTourneau (USN), Flt Lt Parker (RAF), Capt Fick, and Capt Kraabel. I thank my wife, Tonya, for her incredible understanding and support—again! Jack, Pete, and Reed (my boys) also provided the necessary laughter and wrestling matches during breaks. And, as in all things, I thank the Lord for seeing me through another chapter of my life.

Michael J. Chapa

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List of Abbreviations, Acronyms, and Symbols (cont.)

Abbreviation	Definition	Unit
α, alpha	Angle-of-Attack	deg
δ_e, de	Elevator Deflection	deg
δ_{e_c}, dec	Elevator Deflection Commanded	deg
$\dot{\delta}_e$, derate	Elevator Rate	deg/sec
$\dot{\delta}_{e_c}$, decrate	Commanded Elevator Rate	deg/sec
$\dot{\delta}_{e_{c_{limit}}}$	Commanded Elevator Rate Limit	deg/sec
$\delta_{e_{c_f}}$, decf	Elevator Deflection Commanded by Filter	deg
δ_{e_p}	Actual Pilot Input to Elevator	deg
$\delta_{e_{p_c}}, \delta_{e_{c_p}}$	Commanded Pilot Input to Elevator	deg
$\ddot{\delta}_e$	Elevator Acceleration	deg/sec^2
$\ddot{\delta}_{e_c}$	Commanded Elevator Acceleration	deg/sec^2
$\ddot{\delta}_{e_{c_{threshold}}}$	Commanded Elevator Acceleration Threshold	deg/sec^2
θ, theta	Pitch Angle	deg
θ_t	Pitch Angle Track Command	deg
e	Pitch Angle Track Command Error ($\theta_t - \theta$)	deg
ω_n	Natural Frequency	rad/sec
ζ, zeta	Damping	--
A/C	Aircraft	--
AFIT	Air Force Institute of Technology	--
deg	Degree(s)	--

List of Abbreviations, Acronyms, and Symbols (cont.)

Abbreviation	Definition	Unit
F_s	Longitudinal Stick Force Exerted by the Pilot	lb
ft	foot, feet	--
HAFA	Highly Augmented Fighter Aircraft	--
HUD	Heads Up Display	--
Hz, Hertz	Cycles Per Second	--
in	inch(es)	--
k_α	Feedback Gain (Multiplier) of Angle-of-Attack	--
k_p	Pilot Gain (Multiplier) in Neal-Smith Pilot Model	--
k_q	Feedback Gain (Multiplier) of Pitch Rate	--
lb	Pound(s)	--
LOES	Lower Order Equivalent System	--
MIL-STD	Miltary Standard	--
PIO	Pilot-Induced-Oscillation	--
q	Pitch Rate	deg/sec
rad	Radian(s)	--
RLPF	Rate Limiter Pre-Filter	--
RMS	Root Mean Square	--
s	Laplacian Operator	rad/s
s, sec	Second(s)	--
SAS	Stability Augmentation System	--
SWRL	Software Rate Limit	
T_2	Time to Double	sec
T_{p_1}, T_{p_2}	Constants for the Modified Neal-Smith Pilot Model	sec
$T_{\theta 2}$	Lower Order Equivalent System Zero Determinant	sec
TPS	Test Pilot School	--

List of Abbreviations, Acronyms, and Symbols (cont.)

Abbreviation	Definition	Unit
VISTA	Variable Stability In-flight Simulator Test Aircraft	--
VSS	Variable Stability System	--
USAF	United States Air Force	--

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Abstract

Closed loop instability caused by excess phase lag induced by actuator rate limiting has been suspected in many aircraft departures from controlled flight and pilot-induced oscillations (PIO). As part of the joint Air Force Institute of Technology/Test Pilot School (AFIT/TPS) program, a nonlinear rate limiter pre-filter (RLPF) was developed to minimize the phase lag induced by rate limiting.

RLPF performance was evaluated inside the feedback path, but primary emphasis was on the pilot command path. Closed loop computer and motion-based flight simulations were conducted to prepare for the flight test. The HAVE FILTER flight test project was flown using the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) aircraft and evaluated using a software rate limit (SWRL) with and without an RLPF on the pilot command path. A programmable heads-up-display (HUD) was used to generate a fighter tracking task.

Flight test results showed the SWRL was useful in preventing departure and/or PIO. However, with low SWRL settings (<40 deg/sec) handling qualities deficiencies were uncovered due to sluggish initial pitch response.

The RLPF plus SWRL combination resulted in more departure and/or PIO protection than the SWRL alone. But, with low SWRL settings (<40 deg/sec) significant handling qualities deficiencies were sometimes found.

A NONLINEAR PRE-FILTER TO PREVENT DEPARTURE AND/OR PILOT-INDUCED OSCILLATIONS (PIO) DUE TO ACTUATOR RATE LIMITING

I. Introduction

General

The purpose of this simulation study and flight test was to reduce the effects of actuator rate limiting on longitudinal departure and/or pilot-induced oscillations (PIO). Rate limiting has been present in many departure and PIO events. Reducing the negative effect of rate limiting may reduce the tendency to depart and/or PIO and therefore preserve assets.

The Air Vehicles Division of Air Force Research Laboratory sponsored this investigation. The simulation study was conducted at the Air Force Institute of Technology (AFIT), the Air Vehicles Division of Air Force Research Laboratory (AFRL), Wright-Patterson AFB, Ohio, and the United States Air Force Test Pilot School (USAF TPS), Edwards AFB, California. The flight test project was flown in the USAF NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) aircraft (S/N 86-0048) from the Calspan Flight Research Facility in Buffalo, New York. Electronic flight

test data is available from the Air Vehicles Division of Air Force Research Laboratory (AFRL), Wright-Patterson AFB, Ohio.

Background

Pilot-induced oscillations (PIO) have been noted in airplanes since the Wright Brothers (McRuer, 1995). Sometimes these events have led to loss of aircraft, or worse, life. MIL-STD 1797A defines PIO as "sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft" (DOD, 1990). This undesired aircraft-pilot coupling (APC—synonymous with PIO) results when tight control is attempted. Through proper design of an aircraft, many PIO causes (mostly linear) can be minimized or eliminated.

PIOs are often sudden or unexpected, and range in severity from annoying to catastrophic (Anderson and Page, 1994; McRuer, 1995; McRuer and others, 1996). Predicting PIO is difficult due to the adaptive nature of the human pilot (Anderson and Page, 1994; Anderson and Page, 1995). The possible consequences of a PIO necessitate the need for analysis by flight control designers.

There appear to be PIO trigger events. These trigger events may not cause the PIO, but are required to excite the system starting the oscillation event. These triggers may include a wind gust, mode switch, or a control system failure (Anderson and Page, 1995).

Mr. Ralph Smith developed much of classical PIO theory (Smith, 1977). He identified three basic types: 1) Type I -- pilot switches from tracking pitch attitude to pilot-felt normal acceleration, 2) Type II -- sudden change in the flight control system or

with transitions. "Category II is...a special amplitude-dependent extended case of Category I, as well as being one of the simplest examples of Category III" (Klyde and others, 1995).

Actuator rate limiting occurs when the input rate to the control surface exceeds the hydraulic and/or mechanical capability of the control surface actuator. In some PIO events the PIO caused rate limiting, rather than rate limiting causing PIO. But control actuator rate limiting is suspected as a common nonlinear effect causing PIO (Mitchell and Hoh, 1995; Anderson and Page, 1995). Unfortunately, this is not totally understood and does not readily appear in linear analysis. Recently, some attempts have been made to check linear prediction techniques in the presence of some nonlinearities (Buckley and others, 1995). Almost all recorded severe PIOs have shown rate limiting. These included the Space Shuttle, YF-22, and JAS-39 Grippen (Duda and Krag, 1995; Klyde and others, 1996; McRuer and others, 1996). In the case of the latter two aircraft, loss of aircraft resulted from a documented PIO in the pitch axis (Durham and Bordignon, 1994).

Rate limiting has been identified with PIO for two main reasons. First, it introduces additional phase lag, or delay, between commanded control surface position (δ_{ec}) and actual control surface position (δ_e). "The response of a rate-limited actuator will lag behind a rapidly changing command. This tends to destabilize the closed-loop system" (Hammet and others, 1994). The time delay caused by the additional phase lag can drive the pilot to compensate with faster inputs, worsening the situation. This can ultimately lead to a PIO or unstable situation. The second reason rate limiting has been identified in PIO is the reduction in gain. The pilot sees this as a reduction in control

effectiveness, so he may compensate with larger inputs making the problem worse. These two rate limiting concepts are shown in Figure 1-1.

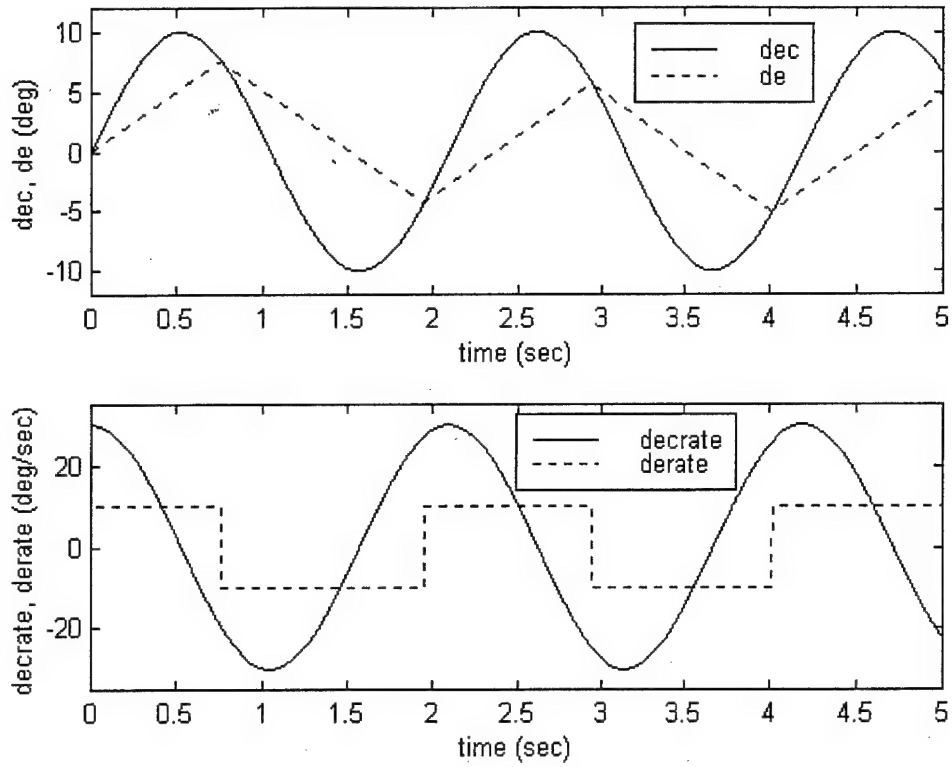


Figure 1-1. Example Time History of Rate Limiting

These effects often mislead the pilot into thinking the aircraft is not responding to his inputs. Of note, the YF-22 mishap pilot stated he "was not aware that he was in a PIO and thought the aircraft had malfunctioned" (Duda and Krag, 1995).

Others believe "there have been indications that it is possible to PIO an otherwise good airplane simply by saturating the actuator rates, and it appears that the result is almost always a severe PIO" (Mitchell and Hoh, 1995). But the results of a recent flight test study (HAVE GRIP) indicate this may not always be true (Peters, 1997). The HAVE

GRIP flight test study noted that low rate limits in certain configurations did not necessarily cause a PIO, just a lack of response.

During rate limiting, the pilot's input is attenuated. One obvious solution is to raise the rate limit of the actuator. But, this means bigger and heavier actuators and McDonnell-Douglas found that for the YF-23, in certain instances, even raising the rate limit of an actuator to 135°/sec alone may still not eliminate susceptibility to PIO (Buckley and others, 1995). Even though loss in gain may be unavoidable, previous analyses have shown that installing a pre-filter before the actuator in an attempt to keep the actuator output closer in phase to the commanded input produced desirable results (A'Harra, 1994; Deppe and others, 1994; Koper, 1987). This concept is demonstrated in Figure 1-2.

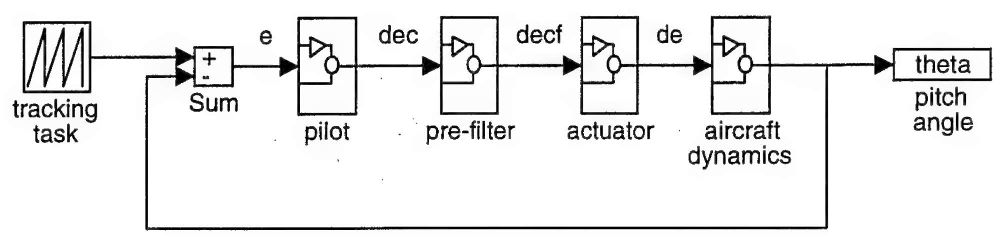


Figure 1-2. Example Actuator Rate Limit Protection Configuration

Reducing the phase lag means the extra time delay due to rate limiting is reduced. One big problem with this design is that for large inputs, or a series of rapidly changing inputs, a bias can develop causing steady state error upon maneuver completion. Also, the derivative--rate limit--integration scheme is susceptible to noise. Differencing noise

may subsequently command rapid changes in the actuator, or ratcheting, which is also undesirable.

Some modern aircraft are designed with output feedback stabilizing an unstable bare airframe (thus enabling reductions in tail size, enhancing low-observability, etc.). During aggressive maneuvering, the pilot plus feedbacks may exceed the rate limit resulting in degradation toward unaugmented dynamics (Buckley and others, 1995). The loss of two JAS-39 Gripen fighter prototypes and the HAVE LIMITS flight test program showed this situation could lead to a sudden, violent departure when the bare airframe was unstable and the there was insufficient or no protection from rate limiting in the loop (Kish and others, 1997). But, "if an unstable process is controlled by a controller with a limited and/or rate limited control signal, an input signal of sufficiently large amplitude will destabilize the closed loop" (Rundqwist, 1996).

One proposed solution has been to software rate limit the pilot's input in an augmented aircraft below the hardware rate limit of the actuator allowing the feedbacks some of the available rate for stabilization. The big question is how much should go to the pilot and how much should go to the feedbacks. As you software rate limit the pilot command, you are potentially decreasing performance and possibly increasing the likelihood of PIO (Leggett, 1997). This may be due to either: 1) not rate limiting the pilot enough and thus saturating the actuator through feedbacks, or 2) rate limiting the pilot too much and producing out of phase stick inputs. The software rate limit concept is demonstrated in Figure 1-3.

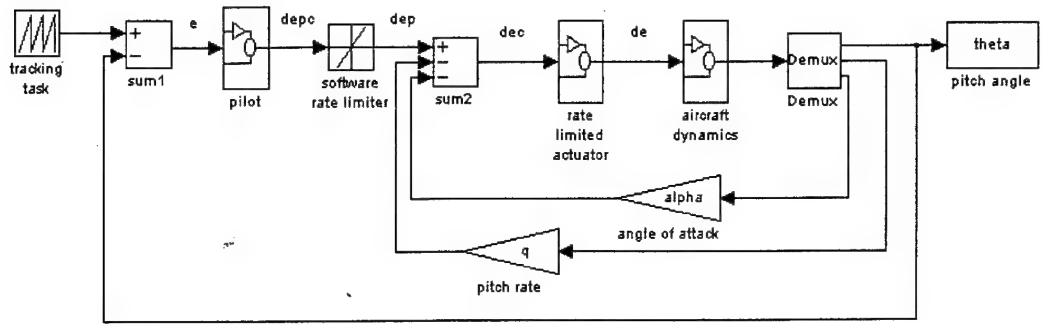


Figure 1-3. Example Pilot Command Path Rate Limit Protection Configuration

Applying a software rate limit to the feedbacks is also possible. But, then you may be further increasing the likelihood of departure and/or PIO for the same reasons just mentioned plus you are limiting the feedbacks required for stability. In addition, every limit in the loop means potential loss in performance. If the purpose is a high-performance fighter, limiting too much may be counter-productive.

However, the JAS-39 Gripen program solution included rate limiters with phase compensation (under patent protection) in the forward and feedback paths. This solution did not use nonlinear logic filters, but rather feedback with bypass. A problem identified with this solution is high frequency disturbances, but favorable pilot comments and confidence in the solution were high enough for production (Rundqwist, 1996).

This study will investigate the effects of varying the software rate limit (SWRL) level on the pilot command as well as seeking improved performance by installing the rate limiter pre-filter (RLPF) in front of the SWRL. Some attention will be given to pre-filtering the actuator inside the feedback loop, but the predominant emphasis will be on

software rate limiting and pre-filtering the pilot command alone outside the feedback loop.

Objectives

The primary objective of this study was to reduce the possibility of actuator rate limiting developing into longitudinal departure and/or PIO. The specific objectives were to:

1. Improve the bias removal and noise problems associated with some previous pre-filters, while still retaining the positive effect of reversing in phase with the input
2. Investigate the performance of using the rate limiter pre-filter (RLPF) inside the longitudinal feedback loop of highly augmented fighter aircraft flight control systems
3. Investigate the performance of using the RLPF on the longitudinal path of unaugmented fighter flight control systems
4. Investigate the performance of using a software rate limit (SWRL) with and without the RLPF on the longitudinal pilot command (outside the feedback loop) of highly augmented fighter aircraft flight control systems
5. Obtain flight test data to assist others in the study of rate limiting as a cause of departure and/or PIO

This investigation was performed in two parts. The first part was a simulation study to determine the feasibility of using the RLPF on the actuator and also using a SWRL with and without the RLPF on the pilot command. These results helped shape the flight test plan which only looked at using the SWRL with and without the RLPF on the

pilot command. The flight test evaluated the concepts developed during the simulation study.

Approach

The following steps were taken for this project:

1. Designed a nonlinear rate limiter pre-filter (RLPF) logic that:
   A. Minimized the phase lag due to rate limiting
   B. Satisfactorily removed the bias that can build up during maneuvering
   C. Handled noise in the loop effectively
2. Started with the HAVE LIMITS 2DU aircraft configuration (Kish and others, 1997)
   A. Developed bare aircraft dynamics
   B. Modified a hydraulic actuator model to include rate limiting
   C. Developed a Modified Neal-Smith pilot model
   D. Analyzed noise from flight test data and injected it in the loop
3. Modified the loop to include digital effects
   A. Delayed all feedbacks and inputs into controller
   B. Set up flight controller to run at different integration time steps than simulation time steps
   C. Converted pre-filter to discrete
4. Varied feedbacks toward a stable unaugmented airframe
5. Studied rate limiting and pre-filter compensation for 1-4 above
   A. Checked rate limiter pre-filter (RLPF) inside feedback loop for actuator rate limit protection

B. Checked software rate limit (SWRL) with and without the RLPF on pilot input for actuator rate limit protection

6. Determined configurations for use during flight test based on simulation results
7. Conducted the flight test

Scope

This research project was very limited in scope. Some of the areas constrained are listed here:

1. The study primarily focused on the pitch axis
2. Tracking tasks were limited to a select few
3. Aircraft configurations were limited to a select few
4. Computer pilot model was limited to the Modified Neal-Smith model
5. Flight test time limited to 14.9 hours per the sponsor's budget

II. Theory

The specifics of the rate limiter pre-filter (RLPF) will be examined in this chapter. This will be followed by a discussion of the aircraft configuration used, along with an explanation of the pilot model used. Noise will then be added. Digitization of the loop is then implemented. Then, feedback gains are varied. Following actuator rate limit protection theory inside the feedback path, actuator rate limit protection on the pilot command path theory is presented.

Rate Limiter Pre-filter (RLPF) Development

This study started with the idea to reverse closely in phase with the input. It was quickly learned that others had done extensive research in this area for ten years or more (A'Harra, 1994; Deppe and others, 1994; Koper, 1987). The big problems with logic pre-filters seemed to be bias removal and noise sensitivity (Deppe and others, 1994; Ohmit, 1994).

If the input signal is filtered by taking its derivative, limiting the rate, and then integrating, the output will reverse in phase with the commanded input. This process can result in a bias that must be removed. This logic is shown in Figure 2-1.

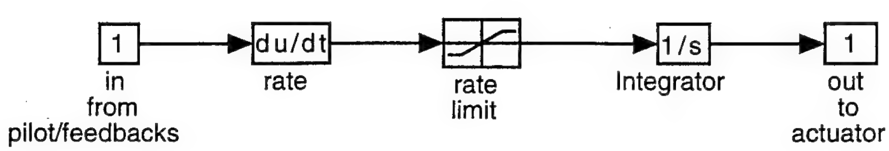


Figure 2-1. Simple Filter Logic

Typical bias development caused by the filter described in Figure 2-1 is shown in Figure 2-2.

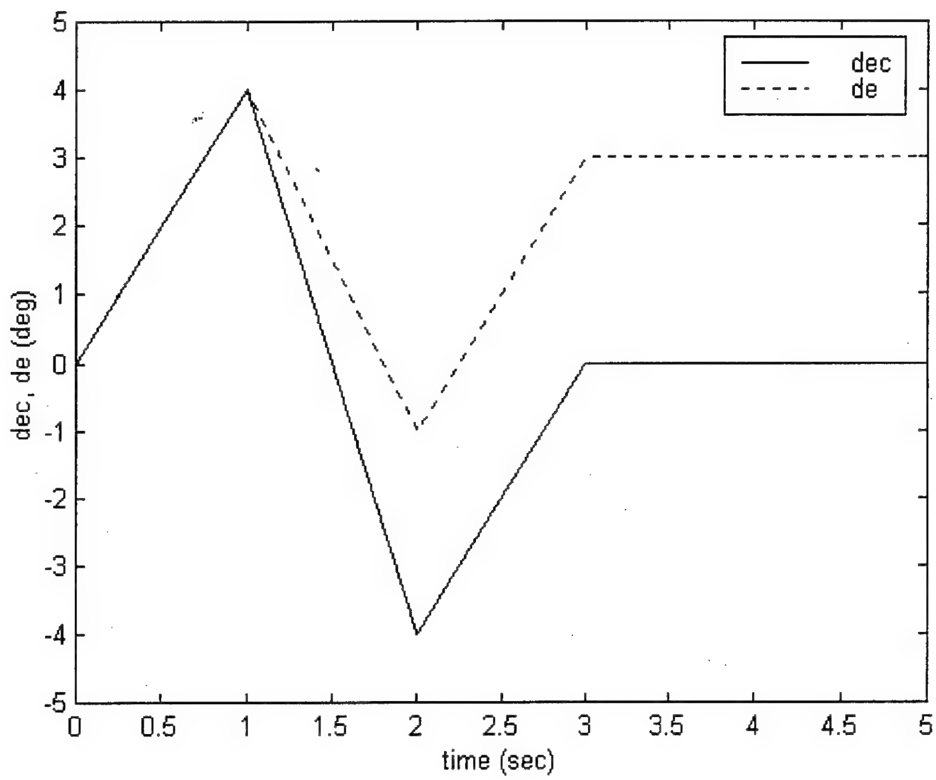


Figure 2-2. Example Bias Development

Different schemes have been tested for bias removal. One study investigated having the pilot manually initiate bias removal after maneuvering which turned out to be unacceptable (Ohmit, 1997). Automatic bias removal following maneuvering during benign conditions appeared to the pilot as an uncommanded input and was also unacceptable (Ohmit, 1994).

In addition, when differencing is used for differentiation, noise entering the pre-filter may frequently and inappropriately cause logic switching. If the RLPF is operating on the actuator inside the feedback path, this produces rapidly reversing actuator

commands, or ratcheting, which is also undesirable. One attempt at handling noise was proven undesirable during flight test in that the pilot was unacceptably gained down (Deppe and others, 1994; Ohmit, 1994).

The RLPF presented in this thesis improves on previous concepts in two ways:

1) Removes bias quickly at the rate limit during maneuvering using a reset integrator thus minimizing large biases at maneuver completion
2) Noise filtering for the switching decision is done off-line to prevent attenuation of the input by the noise filter

Next, the specifics of the filter are presented.

This RLPF switches between the commanded input and a rate limited input, instead of continuously filtering the input. The RLPF attempts to send the commanded input through clean whenever possible. Now, in order to reverse closely in phase, the RLPF looks at not only the first derivative, but also looks at the second derivative to determine that the command is reversing. If only the first derivative was analyzed, the RLPF would not command as quick a reversal during rapid maneuvering. Although susceptible to unfiltered noise, using filtered first and second derivative information enables an earlier reversal than just looking for the rate limit being reached.

Although filtering high frequency noise off-line prevents any attenuation, the switching decision is delayed due to the phase lag incurred by the noise filter. This is counter-productive, but was seen as unavoidable, and is recovered somewhat by using the second derivative information.

Any bias is removed by the RLPF whenever the clean input is chosen. This is effected at the rate limit (hardware or software rate limit depending on location of filter in

the loop), thus removing bias at the fastest possible rate. The RLPF logic is shown in Figure 2-3. Note that the reset integrator uses the actuator output for resetting during bias removal.

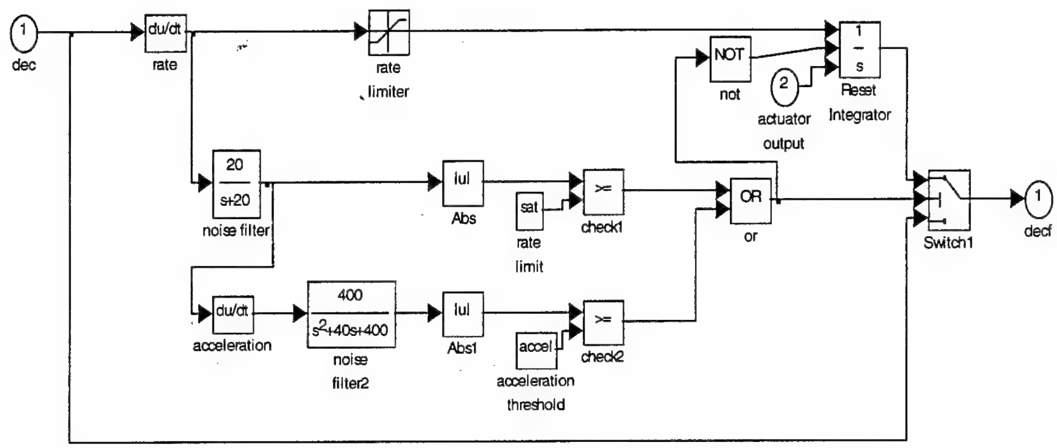


Figure 2-3. Rate Limiter Pre-Filter (RLPF)

As can be seen in Figure 2-3, the input signal splits and selects the filtered signal when:

a) $\dot{\delta}_{e_c} \geq \dot{\delta}_{e_{c_{limit}}}$

or

b) $\ddot{\delta}_{e_c} \geq \ddot{\delta}_{e_{c_{threshold}}}$

The RLPF reversal and bias removal capabilities are demonstrated in Figure 2-4. The difference between using first derivative only information with using both first and second derivative information is clearly demonstrated.

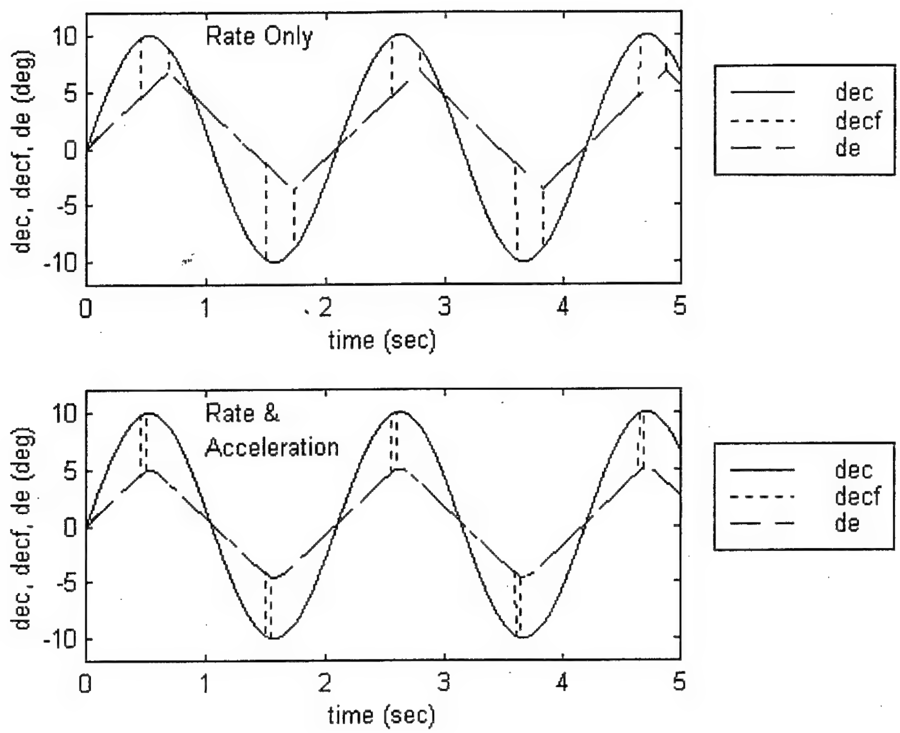


Figure 2-4. Switching Logic Comparison

The acceleration threshold was empirically determined to work best in SIMULINK™ around 50°/sec^2 (dependent on the noise level present in the loop), but has mixed consequences. The filter reverses better with a lower acceleration threshold, but the likelihood of sending through a clean non-rate limited input is lowered and bias removal degrades due to noise. That is, the filter may have trouble removing bias due to large acceleration values caused by noise, not the input. Conversely, if the acceleration threshold is set too high, the reversal is delayed and the filter does not reverse in phase as well.

Another version of the filter included looking at the sign of the rate and acceleration to more accurately determine reversals. However, that design proved less effective during simulation and was abandoned.

Aircraft Development

The 2DU aircraft configuration used in this study comes from the HAVE LIMITS flight test program from spring 1997. Shown in Figure 2-5 is the 2DU SIMULINK™ diagram provided by CALSPAN:

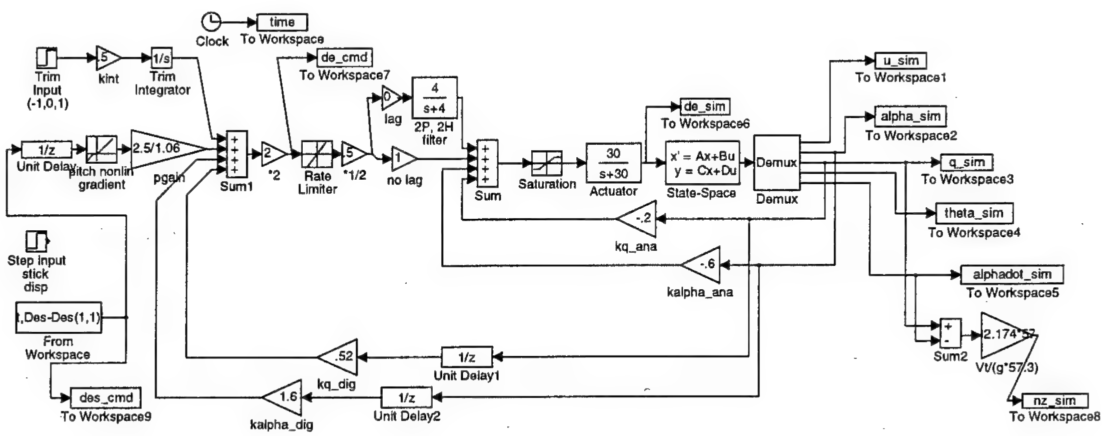


Figure 2-5. NT-33 2DU HAVE LIMITS Configuration

This thesis will not attempt to explain every block in the above diagram, but will hit the highlights to explain how it was modified. This configuration was flight tested on the NT-33 Variable Stability System (VSS) in-flight simulator under the HAVE LIMITS USAF TPS project (the NT-33 is now retired). The bare NT-33 dynamics (phugoid and short period) were computed using defaults in CALSPAN's MATLAB™ lin_abcd.m file in Appendix A. The pitch angle-to-elevator input transfer function approximation is

listed below using shorthand notation where gain is a number, (r) depicts a real root of the form $(s+r)$, and $[\zeta, \omega_n]$ depicts a complex root of the form $(s^2 + 2\zeta\omega_n s + \omega_n^2)$:

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-11.1(1.26)(0.04)}{[0.21,0.08][0.60,2.52]}$$

The modified actuator used in the NT-33 could handle 157 deg/sec, but for computer simulation it was unlimited and the limit was placed on the actuator model placed between the feedback paths (explained later). For computer simulation, the following second order approximation was used for the inner loop NT-33 actuator model (updated from the first order approximation shown in the previous SIMULINK™ diagram):

$$\frac{\delta_e(s)}{\delta_{e_c}(s)} = \frac{75^2}{[0.7,75]}$$

The aircraft used an analog feedback inner loop (angle of attack (α), and pitch rate (q)) to define basic simulated aircraft dynamics (in the case of 2DU it was unstable) and used a digital outer loop of feedback gains (also α and q) to stabilize the plant. The feedback values for the loop closures were obtained from CALSPAN and are listed below:

inner loop: $k_\alpha = -0.6$ $k_q = -0.2$

This gives the dynamics listed below (note the unstable short period with a time to double, T_2, of 0.5 sec):

$$\frac{\theta(s)}{\delta_{e_c}(s)} = \frac{-62354.32(1.26)(0.04)}{[0.25,.07](-1.34)(2.27)[0.70,76.51]}$$

For HAVE LIMITS, a software adjustable rate limit of infinite bandwidth was installed between the outer feedback loop and inner feedback loop to evaluate rate limiting. For early computer simulation in this thesis, however, a first order adjustable

rate limited actuator model was used (see Figure 2-6) with the following dynamics (Stephens and Lewis, 1992):

$$\frac{\delta_e(s)}{\delta_{e_c}(s)} = \frac{20.2}{(20.2)}$$

For use in the MATLAB™ SIMULINK™ environment, rate limiting was introduced by:

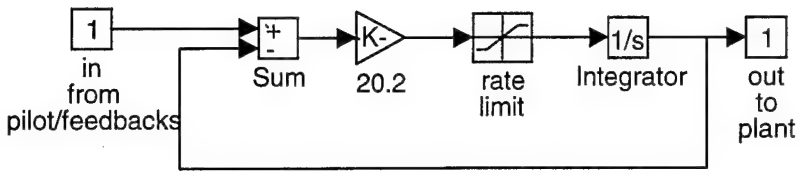


Figure 2-6. Rate Limited Actuator Model

The outer loop digital feedbacks were:

$k_\alpha = +1.6 \qquad k_q = +0.52$

This results in the overall plant dynamics listed below:

$$\frac{\theta(s)}{\delta_{e_c}(s)} = \frac{-1259557.27(1.2)(0.04)}{[0.21,0.08][0.59,5.96](11.78)[0.71,77.19]}$$

Note that in the absence of rate limiting this aircraft is stable. The Neal-Smith prediction for this aircraft (without the first order rate limited actuator model) was level 2 for a fighter tracking task, but the HAVE LIMITS team used other prediction techniques that predicted level 1. Flight test results showed a mixed level 1/level 2 rating in the absence of rate limiting (Kish and others, 1997). The NT-33's stick pitch nonlinear gradient is detailed in Figure 2-7.

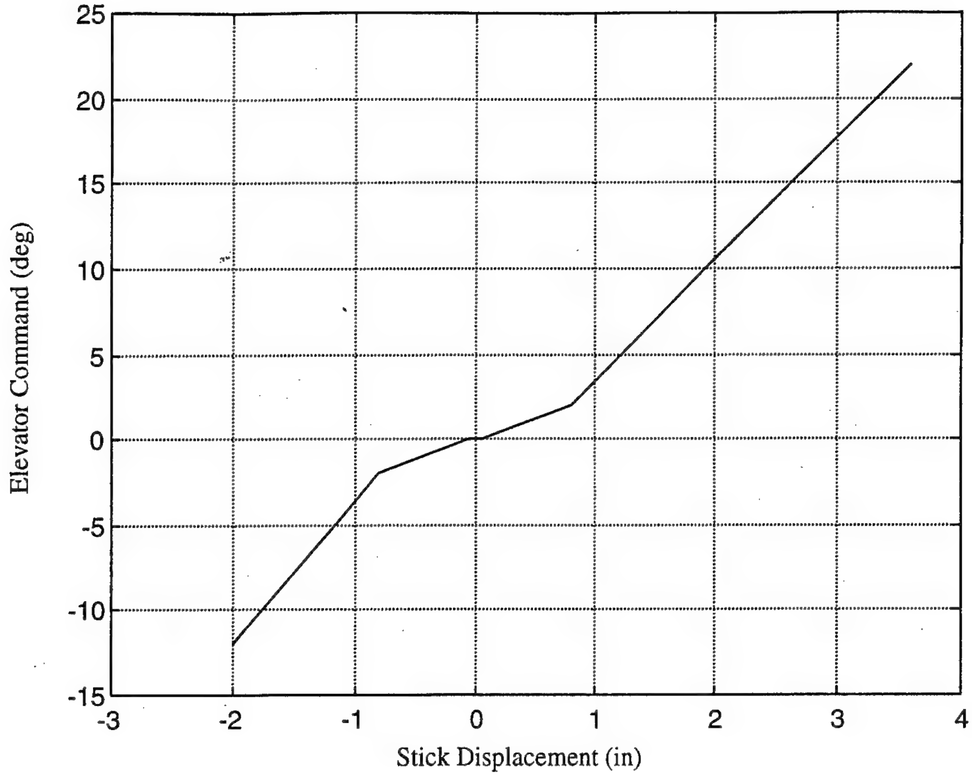


Figure 2-7. NT-33 Pitch Stick Nonlinear Gradient

This gradient presented a problem for linear pilot modeling, so a linear gain approximation was made using the inner region slope of about 2.5 where most tracking inputs will occur. The outer breaks in the nonlinear gradient occur at large inputs making the inner region a good approximation for the tracking task (Ohmit, 1997). There is also an analog-to-digital gain of 2.36 (2.5/1.06) just prior to the outer loop summing junction. Incorporating these two gains into the plant brings the total system gain to -7431389.9.

Pilot Model Development

MIL-STD 1797A describes the Modified Neal-Smith pilot model often used in computer simulation of closed loop pilot/aircraft tracking (DOD, 1990). This model is

based upon achieving certain desired closed loop bandwidths. The required bandwidth is dependent on the phase of flight:

Category A: 3.5 rad/sec

Category B: 1.5 rad/sec

Category C: 1.5 rad/sec (Landing 2.5 rad/sec)

Category A includes such arenas as air-to-air combat, in-flight refueling, and close formation flying, Category B flight includes climb, cruise, and descent, and Category C includes takeoff, approach, and landing. Since this study will be dealing with up-and-away tracking, the Category A Modified Neal-Smith pilot model was used.

The aircraft transfer function was used to derive the Modified Neal-Smith pilot model as defined in MIL-STD 1797A using the Wright Laboratory Flight Control Division's MATLAB™ Handling Qualities Toolbox (Doman and Kish, 1995). The Modified Neal-Smith pilot model has a transfer function of the following form:

$$\frac{\delta_{e_c}(s)}{\theta(s)} = \frac{k_p(5s+1)(T_{p_1}s+1)e^{-0.25s}}{s(T_{p_2}s+1)}$$

where k_p = pilot gain
T_{p_1} = lead required
T_{p_2} = lag required
$e^{-0.25s}$ = neuromuscular delay (empirically determined)

and the $(5s+1)/s$ term comes from the requirement of the pilot to provide low level integration because the aircraft does not have a free s in it. There are no limitations on the values of k_p, T_{p_1}, or T_{p_2}. The pilot must take on the following values in order to achieve the required bandwidth and minimum closed loop resonance for this system:

$k_p = -0.047$ $\quad\quad T_{p_1} = 0.0073$ $\quad\quad T_{p_2} = 0$

Note that this leads to an improper transfer function for the pilot. SIMULINK™ will not accept an improper transfer function so an additional 100/(s+100) was added to the pilot model, resulting in a new k_p of -0.17 (after conversion to pole/zero form). The Nichols chart in Figure 2-8 was generated from the nspilot.m MATLAB™ file in appendix A and is for the combined pilot/aircraft (Y_pY_c) system including the 100/(s+100) term:

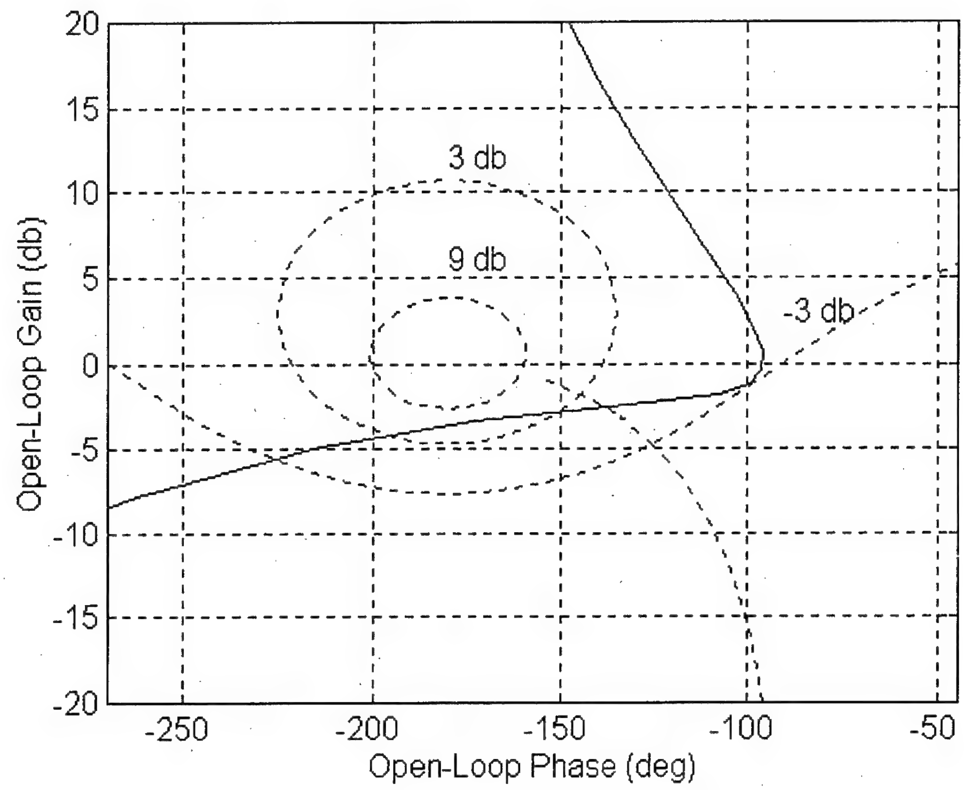


Figure 2-8. Nichols Chart for Modified Neal-Smith Pilot Model

Note that by this closed loop criteria the aircraft is predicted to be Level 2 (DOD, 1990). Attempts to achieve Level 1 were unsuccessful.

Now, the Modified Neal-Smith pilot model was developed to simulate a pilot during a tracking task and may not simulate him well during a PIO. The purpose of the

pre-filter is to prevent PIO, so the bang-bang pilot model developed by Ralph Smith to simulate a pilot already in a PIO was purposely not chosen (Smith 1995; Smith 1994). McRuer believes a pilot is thought to act as pure gain during a PIO (1995). There are other pilot modeling techniques, but the Modified Neal-Smith pilot model was chosen for the computer simulation portion of this thesis, partly for its closed loop criteria and flexibility. Regardless of pilot model chosen, it is still a model and cannot define a human being in all circumstances at all times and is therefore a limitation. Attempts to correlate pilot model results with human piloted flight simulation and test will be made in later chapters.

Stick and Feedback Noise

Internal noise proved to be a factor in a previous pre-filter study (Deppe and others, 1994; Ohmit, 1994). One of their flight test studies artificially injected noise with only 0.01° RMS which prevented successful bias removal (Deppe and others, 1994). Using flight test strip data from the HAVE LIMITS program (Flight 5365, 1997) the NT-33 unfiltered stick noise RMS during a quiescent period was estimated to be 0.3° (0.05 in). According to CALSPAN, stick inputs were noise filtered prior to loop injection in the NT-33, leaving the resultant noise unknown (Ohmit, 1997). The content of resultant noise from the feedbacks was also unknown. What the true noise level from the stick/feedbacks entering the controller is unknown. For most of this simulation, a band-limited normally distributed noise with an RMS of 0.1° was used. Other noise levels were also investigated.

Digital Effects

Figure 2-5 includes digital effects of the pilot's input and feedbacks by using the unit delay block. By running the integration step size in SIMULINK™ at the same speed as the unit delay neglects high frequency dynamics.

The NT-33 flight computer operated both the simulation and the heads-up-display (HUD) and was limited to 45 Hz (time step 0.022 sec). The F-16 digital flight computer runs at approximately 64 Hz (time step 0.0156 sec). With advances in computer capability, future aircraft may run at 80 Hz (time step 0.0125 sec) or even higher.

For this simulation, runs were made at all three flight controller speeds and different integration time steps attempting to analyze the numerical and digital effects on both the aircraft and the pre-filter (RLPF). The highest frequency set of poles is from the actual NT-33 actuator with a natural frequency of about 77 rad/sec (ignoring the $100/(s+100)$ adjustment from the Neal-Smith pilot model). In order to account for these dynamics, integration should be accomplished in the simulation at least twice as fast as these poles (Nyquist frequency), or $1/(2*77) = 0.0065$ sec. This will be investigated further in the next chapter.

In order to incorporate digital effects into the RLPF, the du/dt box was converted to discrete and is shown in Figure 2-9:

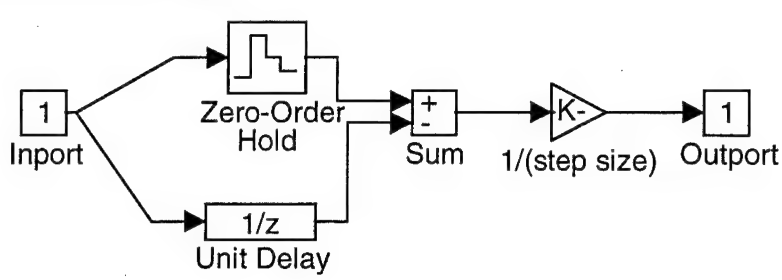


Figure 2-9. Discrete Derivative

The noise filters were converted to discrete using the appropriate time step and Tustin option in MATLAB™. The reset integrator was converted to discrete using the discrete reset integrator option in SIMULINK™ 2.1. The final RLPF discrete design is depicted in Figure 2-10:

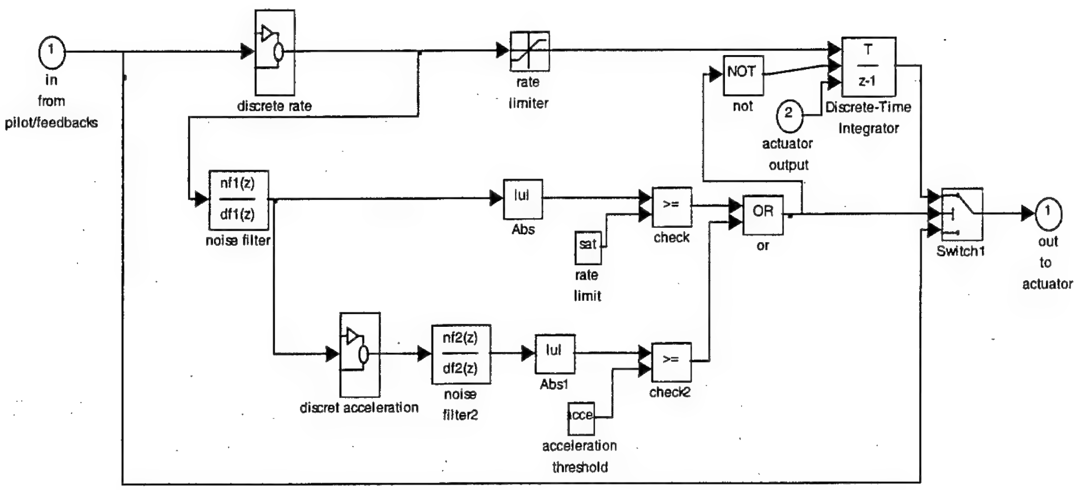


Figure 2-10. Discrete RLPF Design

Actuator Rate Limit Protection Inside the Feedback Path

With all modifications explained in the last section, the configuration used for computer simulation of the RLPF operating inside the feedback path is shown in Figure 2-11.

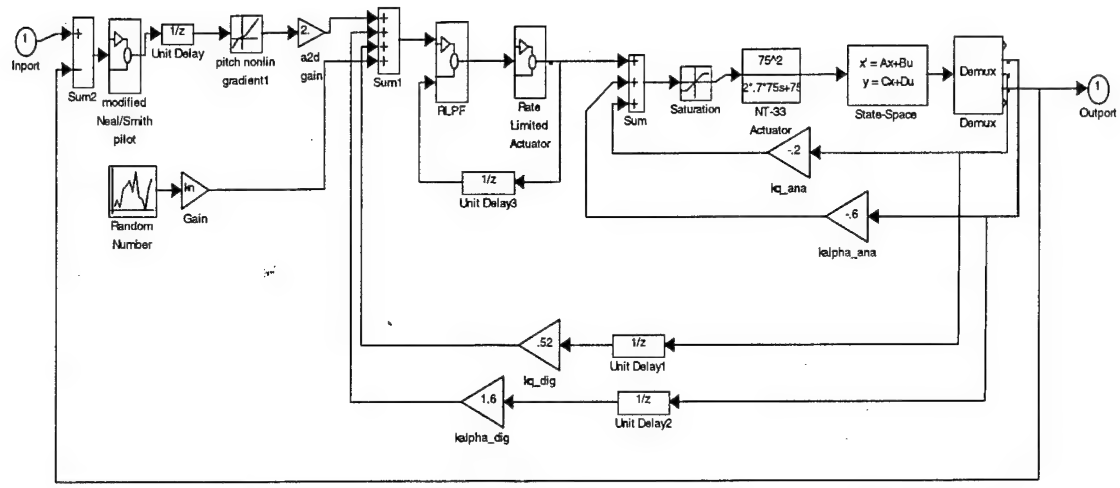


Figure 2-11. Actuator Rate Limit Protection Inside the Feedback Path

This configuration was also used for various feedback options explained in the next section. Simulations were accomplished with and without the RLPF for comparison. Results of simulation are shown in the next chapter.

Augmentation Feedback Gains

For the 2DU configuration, the outer loop stabilizes the unstable inner loop. By moving some/all of the outer loop gains into the inner loop, the net aircraft dynamics remain the same, but the bare (inner loop) simulated aircraft dynamics improve. By moving all the k_q feedbacks to the inner loop, the inner loop dynamics become:

$$\frac{\theta(s)}{\delta_{e_c}(s)} = \frac{-62354.32(1.26)(0.04)}{(-0.04)(0.092)(0.68)(6.40)[0.70,72.32]}$$

which is still unstable, but not nearly as much (previous $T_2 \approx 0.5$ sec, now $T_2 \approx 16$ sec). The augmented system now is more stable in the presence of rate limiting. The expected

result is a more gradual move toward PIO or instability. This configuration, named 2DM, will be investigated in the next chapter.

By moving all k_α feedback to the outer loop and adjusting the inner loop $k_q = -0.2$, the inner loop dynamics become:

$$\frac{\theta(s)}{\delta_{e_c}(s)} = \frac{-62354.32(1.26)(0.04)}{[0.15,0.11][0.23,1.84][0.70,76.53]}$$

This system is stable and is named 2DS. As discovered in the HAVE LIMITS project, low rate limits will not necessarily cause a PIO/unstable situation, but may only result in a lack of pitch response (Peters, 1997). This system is also investigated in the next chapter.

Actuator Rate Limit Protection on the Pilot Command Path

The previous discussion on rate limit protection discussed the hoped for improvements provided by the RLPF when the actuator is saturated. Since this situation is undesirable and maybe unacceptable, an attempt to keep the actuator out of saturation is desirable. Air Force Research Labs (AFRL/VAAI) proposed solution was to place a software rate limit (SWRL) on the pilot command path as the only means of protection. The RLPF can readily be adapted to operate with a SWRL as shown in Figure 2-12.

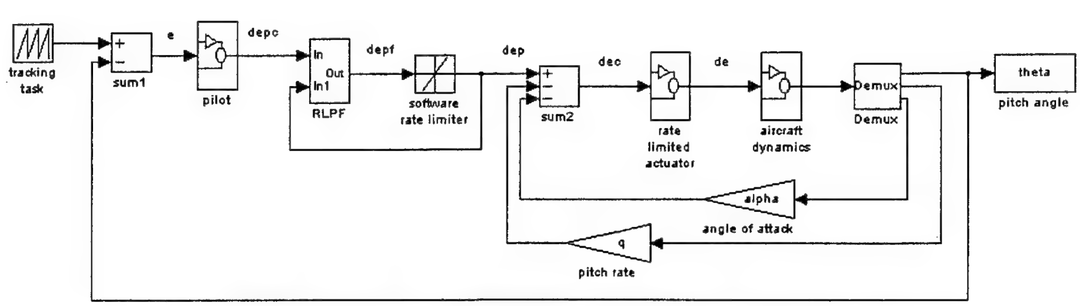


Figure 2-12. Pilot Command Path Rate Limit Protection Configuration

The software rate limit is set below the actuator rate limit allowing the feedbacks some rate to prevent actuator saturation. The RLPF is placed in front of the SWRL to reverse in phase with the pilot's inputs, thus removing any phase lag added to the loop by the SWRL. The nonlinear nature of the problem drives the requirement to have a SWRL low enough to prevent actuator rate limiting causing departure and/or PIO, but if the SWRL is set too low, significant deficient handling qualities may arise. The RLPF should help by either:

1) allowing a larger software rate limit setting thereby increasing performance
2) reducing any current SWRL setting's tendency to depart and/or PIO or, at the very least, result in less a violent PIO

Simulation and flight test comparisons between the SWRL only configuration shown in Figure 1-3 and the RLPF plus SWRL configuration shown in Figure 2-12 are discussed in chapters 4 through 6.

In summary, this chapter has laid the theoretical background for the Rate Limiter Pre-Filter (RLPF), the 2DU aircraft model including loop noise and digital effects, and the Modified Neal-Smith pilot model used in computer simulation. Two different applications for the RLPF were presented. The first application for the RLPF was inside the feedback path operating on the rate limited actuator. In addition to the 2DU aircraft model, two other aircraft models, 2DM and 2DS, were developed by varying the feedback gains of the inner loop. The second application for the RLPF was on the pilot command path operating on a software rate limit (SWRL). Simulation and flight test results are presented in chapters 3 through 6.

III. Inner Loop Actuator Rate Limit Protection Simulation Results

Computer simulation and Large Amplitude Multimode Aerospace Simulator (LAMARS) results with the RLPF operating on the actuator inside the feedback path will be presented in this chapter. Computer simulation results include: 1) continuous simulation, 2) digital simulation including three controller speeds (45 Hz (0.022 sec delay), 64 Hz (0.0156 sec delay), and 80 Hz (0.0125 sec delay)), and 3) varying feedbacks. The LAMARS results are for a 64 Hz controller.

Continuous Simulation

These results come from the Figure 2-11 configuration in chapter two without the unit delays and used the continuous RLPF shown in Figure 2-3. Several tracking tasks were evaluated with a $\pm 4^{\circ}$ doublet presented here. Noise was injected at 0.1° RMS. Simulations were started with the actuator model between the feedback paths set at 200°/sec rate limit (virtually non-rate limited) with subsequent runs having lower values of rate limiting (in increments of 5°). Since the 2DU configuration was unstable stabilized with feedback, the system could depart suddenly without PIO.

Obviously, these were not true continuous simulations in that MATLAB™ must numerically integrate towards the solution. The continuous nature here was similar to an analog flight controller. Continuous simulation results will be presented in tabular form augmented with plots. It was expected the digital simulation would be closer to reality. First, the comparison between non-rate limited systems (200°/sec) under continuous (no delays) simulation at 0.0022 sec time step for integration is shown in Figure 3-1. This

speed allowed capture of the fastest system dynamics (recall the NT-33 actuator poles at about 77). Note the lower RMS track error with the RLPF in place.

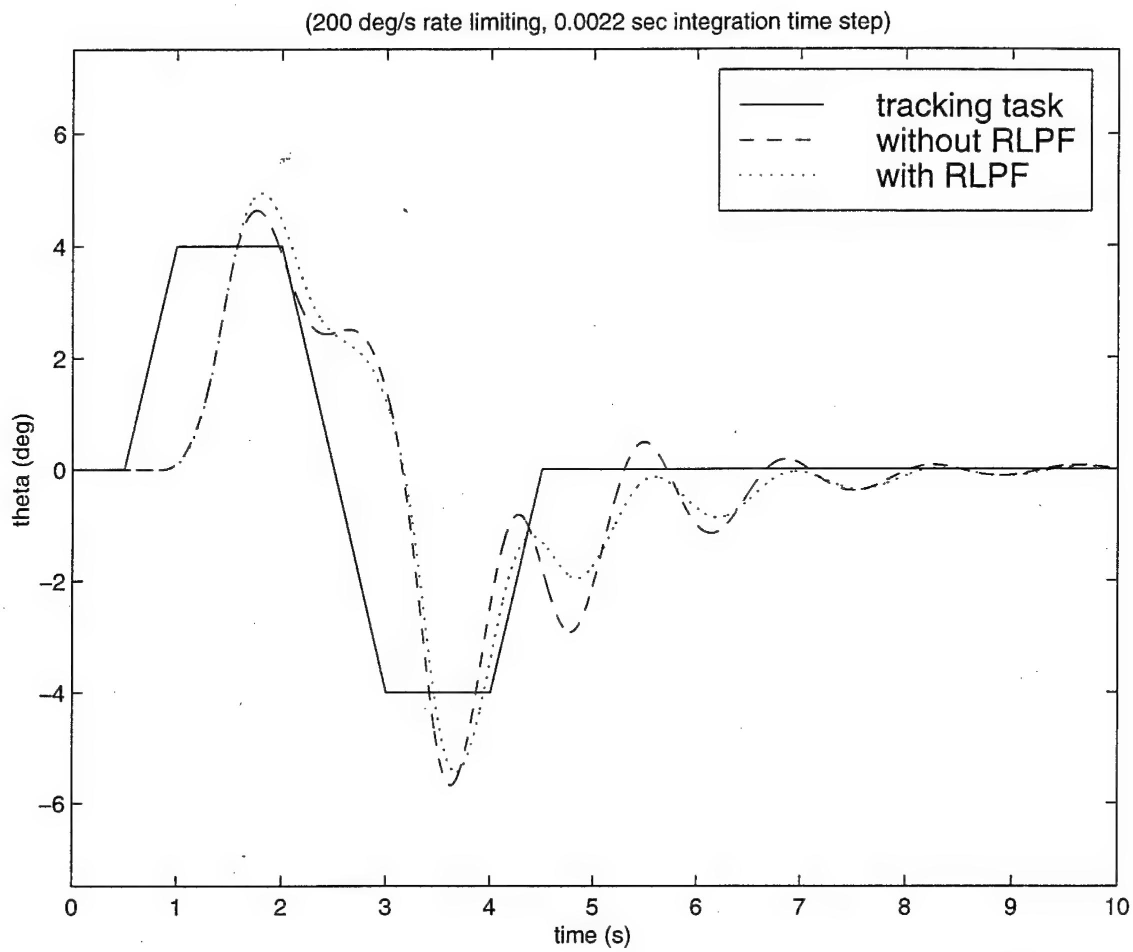


Figure 3-1. Non-rate Limited Continuous Doublet Response (SIMULINK™)

Simulation integration was done at a slow speed neglecting fast dynamics and also at 10x the slow speed, thereby effectively capturing the fast dynamics as discussed in chapter 2. How far the systems can track without going unstable due to rate limiting is shown in Table 3-1.

Table 3-1. Limit of Stability for First Continuous Simulation (SIMULINK™)

	0.022 Integration Step Size	0.0022 Integration Step Size
Without RLPF	35°/sec	35°/sec
With RLPF	25°/sec	20°/sec

A 30°/sec rate limit with 0.0022 sec integration step size example is shown in Figure 3-2.

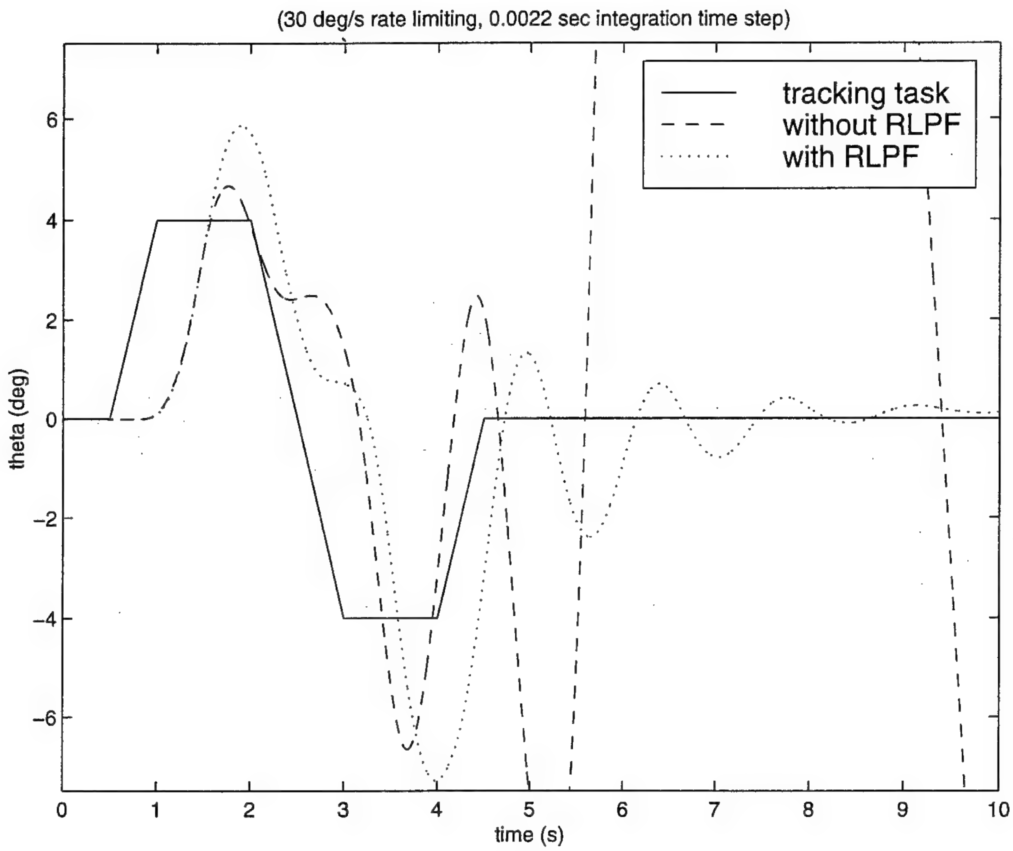
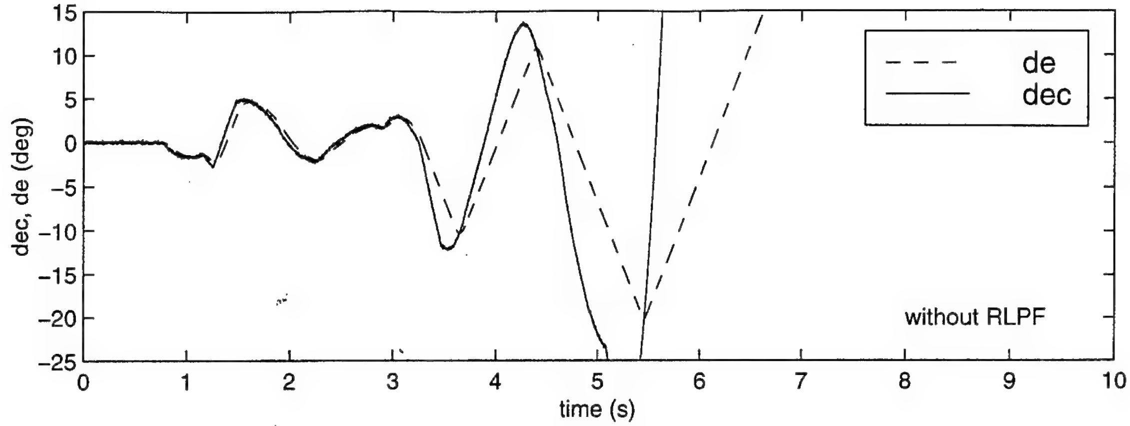


Figure 3-2. 30 deg/sec Rate Limited Continuous Doublet Response (SIMULINK™)

What is going on inside the RLPF is shown in Figure 3-3. Two graphs are presented, the first plot shows the input and output of the rate limited actuator without the RLPF, while the second plot shows the input and output of the rate limited actuator, but also shows the output of the RLPF, $\delta_{e_{cf}}$. This enables analysis of the switching logic.



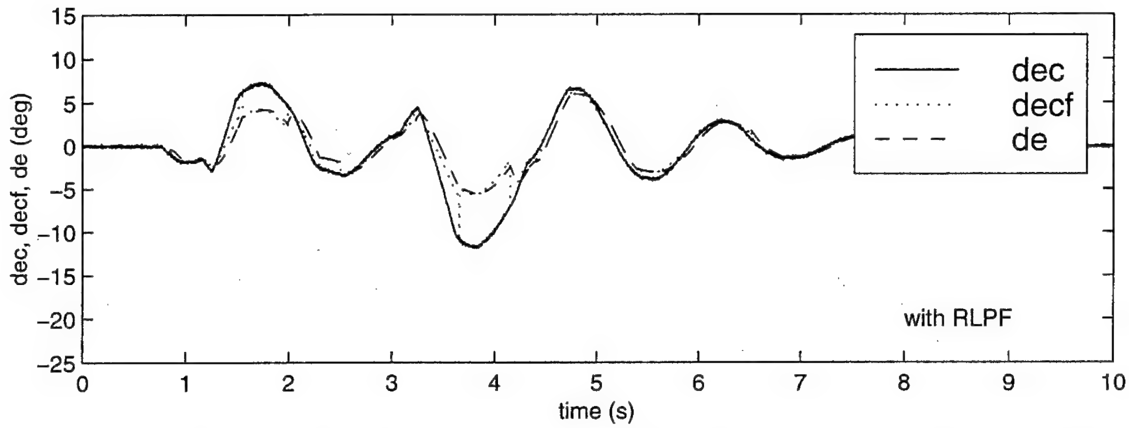


Figure 3-3. 30 deg/sec Rate Limited Actuator w/0.0022 sec time step (SIMULINK™)

As can be seen in Figure 3-3, rate limiting drives the system without the RLPF in place unstable, while the RLPF system stays in phase during rate limiting and prevents the system from going unstable. Changing the integration step size changed the results slightly as depicted in Table 3-2.

Table 3-2. Limit of Stability for Second Continuous Simulation (SIMULINK™)

	0.0156 Integration Step Size	**0.00156 Integration Step Size**
Without RLPF	35°/sec	35°/sec
With RLPF	20°/sec	20°/sec

A final change in integration step size also provided similar results (see Table 3-3).

Table 3-3. Limit of Stability for Third Continuous Simulation (SIMULINK™)

	0.0125 Integration Step Size	0.00125 Integration Step Size
Without RLPF	35°/sec	35°/sec
With RLPF	20°/sec	25°/sec

Although there are slight variations in the results above, a trend is obvious. The RLPF improved the performance during rate limiting under continuous simulation, but might not prevent the system from going unstable if actuator rate limits are too low.

Digital Simulation

The same tracking task and noise RMS value were used for the digital simulation. The big difference here was the inclusion of delays on the inputs to the controller which simulate digital effects. Now, the inner loop and overall integration of the system is updated at one speed, while the outer loop (effectively the flight controller) is updated at a different speed. Simulations were performed at three controller speeds (45 Hz, 64 Hz, and 80 Hz) and at two different integration/inner loop speeds (1x and 10x the controller speed as in continuous simulation). It was expected the 10x speed inner loop would reflect the closest to reality by taking all dynamics into play. Also, increasing controller speed was expected to improve performance.

The non-rate-limited case of 200°/sec is shown in Figure 3-4. All six combinations of controller and integration speed are presented. The first column represents an integration step size equal to the controller speed (ignoring digital effects and fast dynamics), while the second column shows a 10x faster integration speed over controller speed. The three rows increase in controller speed at 45 Hz, 64 Hz, and 80 Hz, respectively.

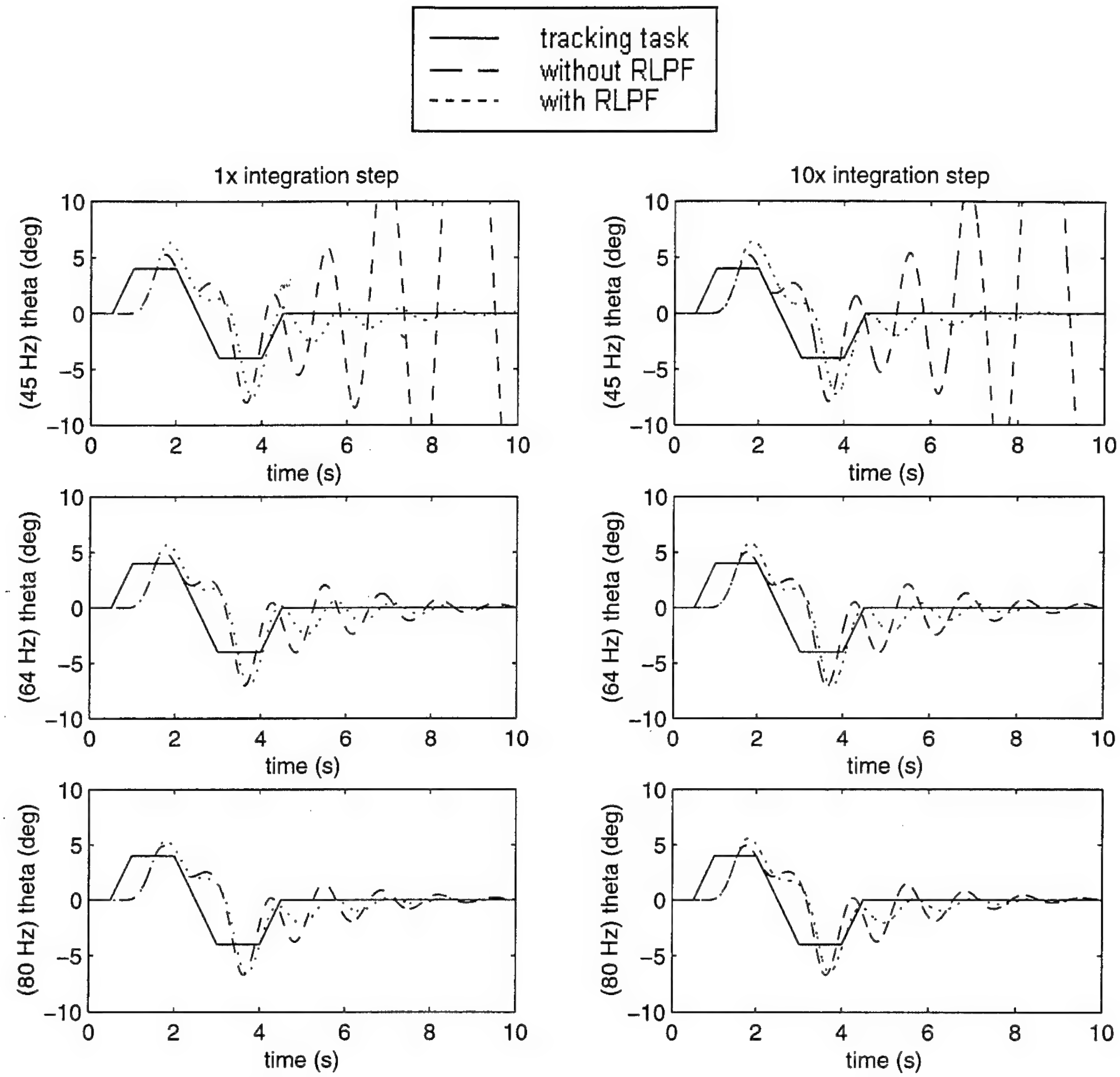


Figure 3-4. Non-rate Limited Digital Response (SIMULINK™)

It is interesting in the above simulation that the 45 Hz system was unable to track without the RLPF. In fact, the top two plots show a classic divergent PIO without the RLPF. As expected, increasing controller speed improved performance.

Digital simulation results comparing controller speed, integration step size, and rate limiting (rate limiting varied in increments of 2.5°) are depicted in Table 3-4. The values represent how severe rate limiting can become before instability.

Table 3-4. Digital Simulation Results (SIMULINK™)

	45 Hz 1x	**45 Hz 10x**	**64 Hz 1x**	**64 Hz 10x**	**80 Hz 1x**	**80 Hz 10x**
Without RLPF	200+°/sec	200+°/sec	50°/sec	50°/sec	45°/sec	45°/sec
With RLPF	70°/sec	55°/sec	30°/sec	30°/sec	45°/sec	42.5°/sec

As can be seen in Table 3-4, increasing controller speed improved performance without the RLPF. With the RLPF in place, substantial improvement is made with a slow 45 Hz controller. At 64 Hz, significant improvement is made. At 80 Hz, however, the improvement was negligible.

In Figure 3-5 the 40°/sec case with a 64 Hz controller at 10x integration speed (time step 0.00156 sec) is shown. The tracking response, actuator response without the RLPF, and actuator response with the RLPF are depicted.

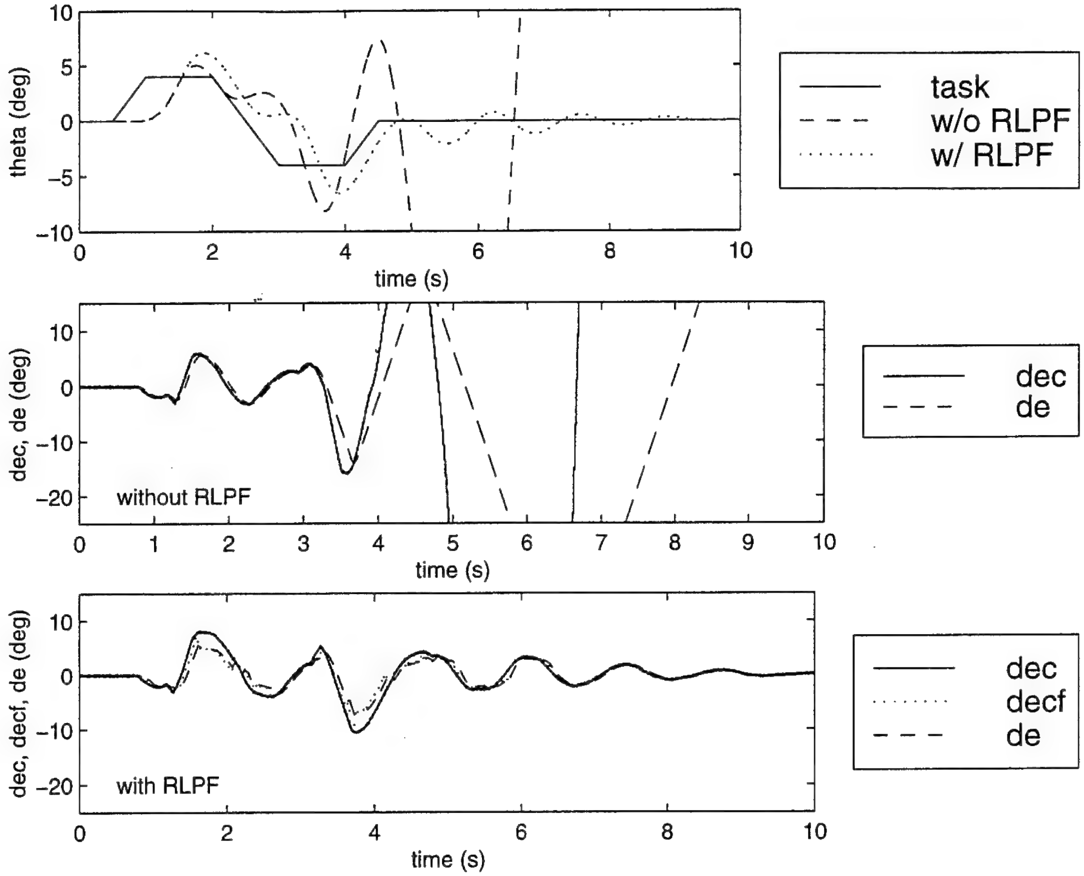


Figure 3-5. 40 deg/sec Rate Limited 64 Hz Digital Response (SIMULINK™)

Varying Feedbacks

By moving all the k_q feedback to the inner loop, the unstable pole moved from -1.34 to -0.044. This more stable configuration was designated 2DM. Note, the dynamics seen by the pilot do not change in the absence of rate limiting, just the inner loop dynamics.

The simulation results showed that it required very low rate limits to drive the unfiltered system unstable. It also showed that the RLPF helped. As noticed in HAVE GRIP, rate limiting itself may not drive the system to PIO (Peters, 1997). The 2DM

tracking results and actuator responses are shown in Figure 3-6 and Figure 3-7. It required a very low 10°/sec rate limit to drive the unprotected 2DM unstable.

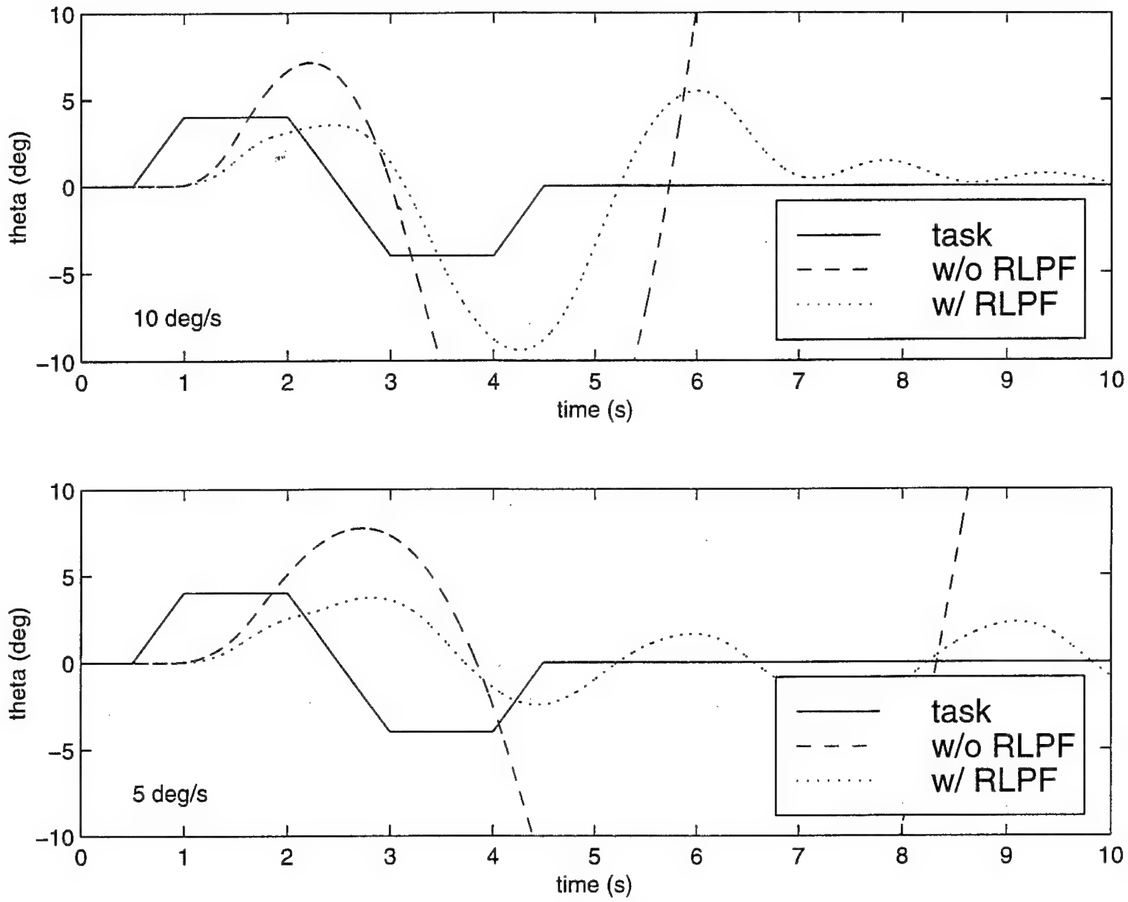


Figure 3-6. 2DM w/64 Hz Controller and 10x Integration (SIMULINK™)

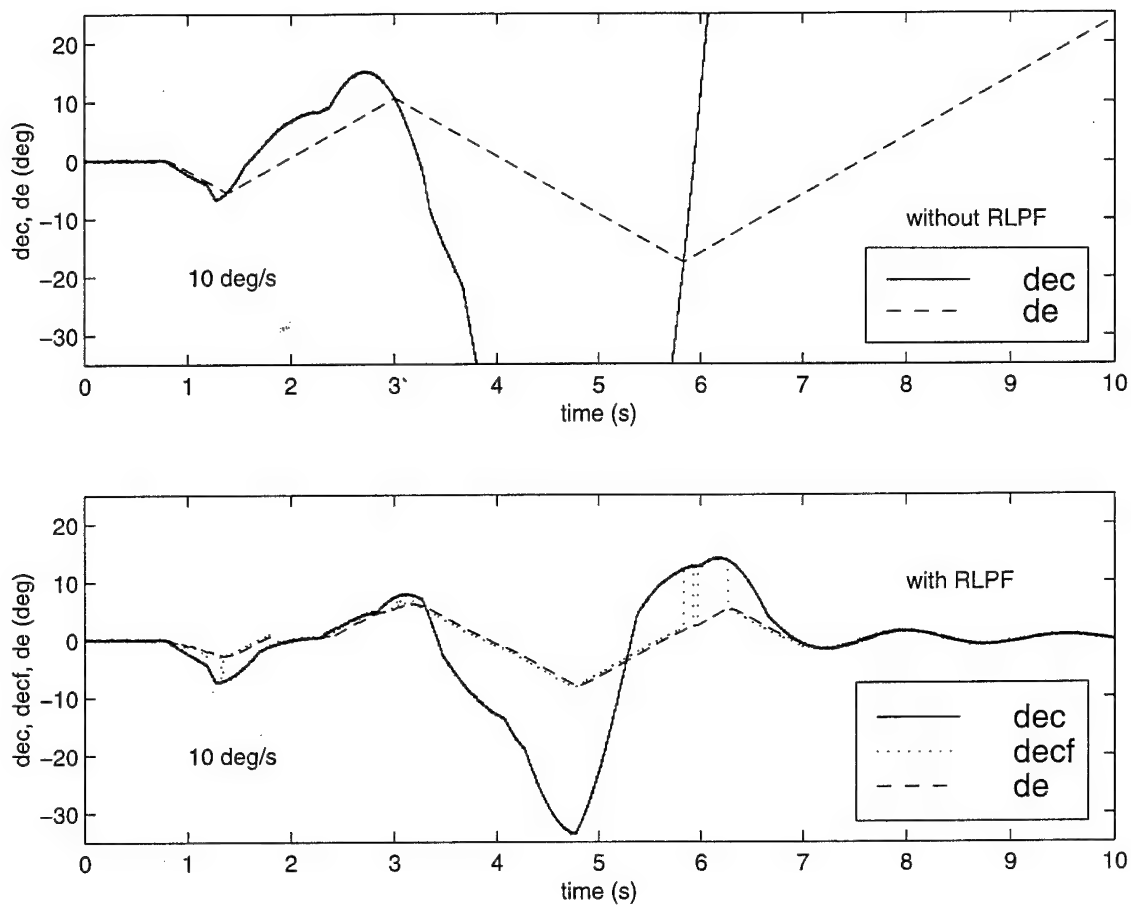


Figure 3-7. Actuator w/64 Hz Controller and 10x Integration (SIMULINK™)

One other configuration was investigated that was *stable* in the inner loop. By moving all k_α gain to the outer loop, the inner loop short period has the following dynamics:

$\zeta = 0.23 \qquad \omega_n = 1.8$

The low damping on the short period requires the outer loop feedback for good aircraft response, but at least the inner loop is stable. The net dynamics are still the same as the previous configurations.

This system was designated 2DS and actually went unstable quicker than 2DM. In this situation, the RLPF system actually went unstable first at 30°/sec, followed by the

non-filtered system at 25°/sec. The following plots in Figure 3-8 are for the 20°/sec case which show the RLPF slightly delaying the instability over the non-filtered system.

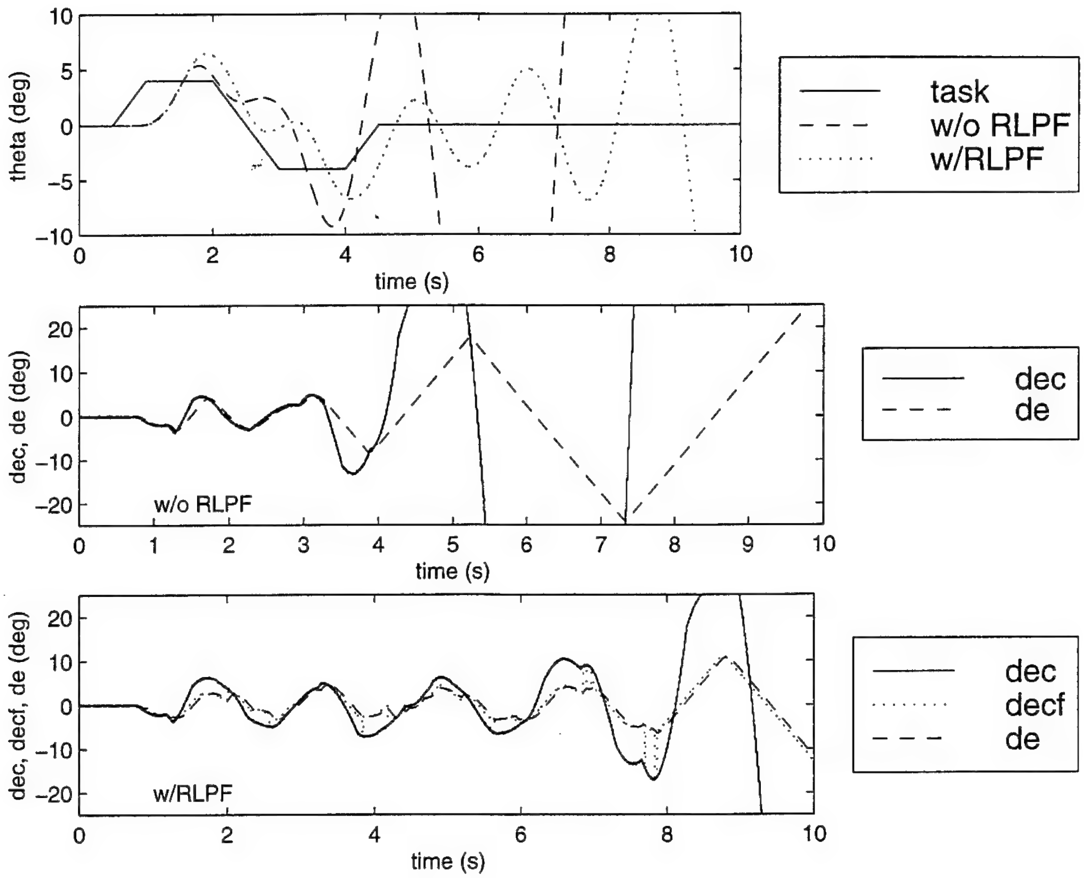


Figure 3-8. 20 deg/sec 2DS w/64 Hz Controller and 10x Integration (SIMULINK™)

Although departure susceptibility improvements were shown under computer simulation with the RLPF inside the feedback path, poor tracking was shown in some cases. Also, computer simulation cannot reveal all handling qualities issues a human pilot may observe. The next section addresses the piloted motion based simulator results where handling qualities were also assessed.

Large Amplitude Multimode Aerospace Simulator (LAMARS) Results

LAMARS is a motion based flight simulator operated by the Air Force Research Laboratory at Wright-Patterson AFB, OH. This simulator offers motion cues to the pilot in addition to visual cues--critical for handling qualities investigations like PIO.

Hardware and software protection applications of the RLPF were tested in LAMARS from 22-30 October 1997. The simulation was set up to run at 64 Hz. The simulator was configured with an F-15 type center stick, F-16 type throttle, and a NT-33 type Heads-Up-Display (HUD). The pilot attempted to follow a target bar on the HUD with a tracking bar. When both bars overlaid each other, there was zero track error. The author, a senior USAF pilot with over 1000 hours flight time in the F-15 and F-16 (HUD equipped aircraft), flew the simulator for the inner loop RLPF tests. An attempt was made to keep the pilot blind to the specific configuration/setting used for each run. HUD audio/video were recorded enabling pilot comments to be matched to the data.

The primary insight gained from LAMARS was that the $50^{\circ}/sec^2$ acceleration threshold in the RLPF used in SIMULINK™ turned out to be unacceptable. For the inner loop RLPF configuration, the acceleration threshold was raised to $200^{\circ}/sec^2$ from $50^{\circ}/sec^2$. This was determined based on pilot comments and filter performance. When the threshold was set higher than $200^{\circ}/sec^2$, the airplane felt loose (recall from chapter two a high threshold may delay reversals and not remove as much phase lag, but a low setting may gain down the input and inhibit bias removal due to noise/high frequency inputs). When the threshold was set lower than $200^{\circ}/sec^2$, the airplane felt sluggish. Individual pilots may have their own thresholding preference.

Using 200°/sec^2 for acceleration thresholding, the actuator rate limit was lowered to investigate RLPF performance. In addition, runs were made without the RLPF in place for comparison. The following figures have three plots on them. The first plot is for the tracking task and theta response. The second plot shows the input and output of the actuator without the RLPF, while the third plot shows the RLPF response integrated with the actuator. The first example (Figure 3-9) is for a actuator rate limit of 60°/sec with lower values of rate limiting following.

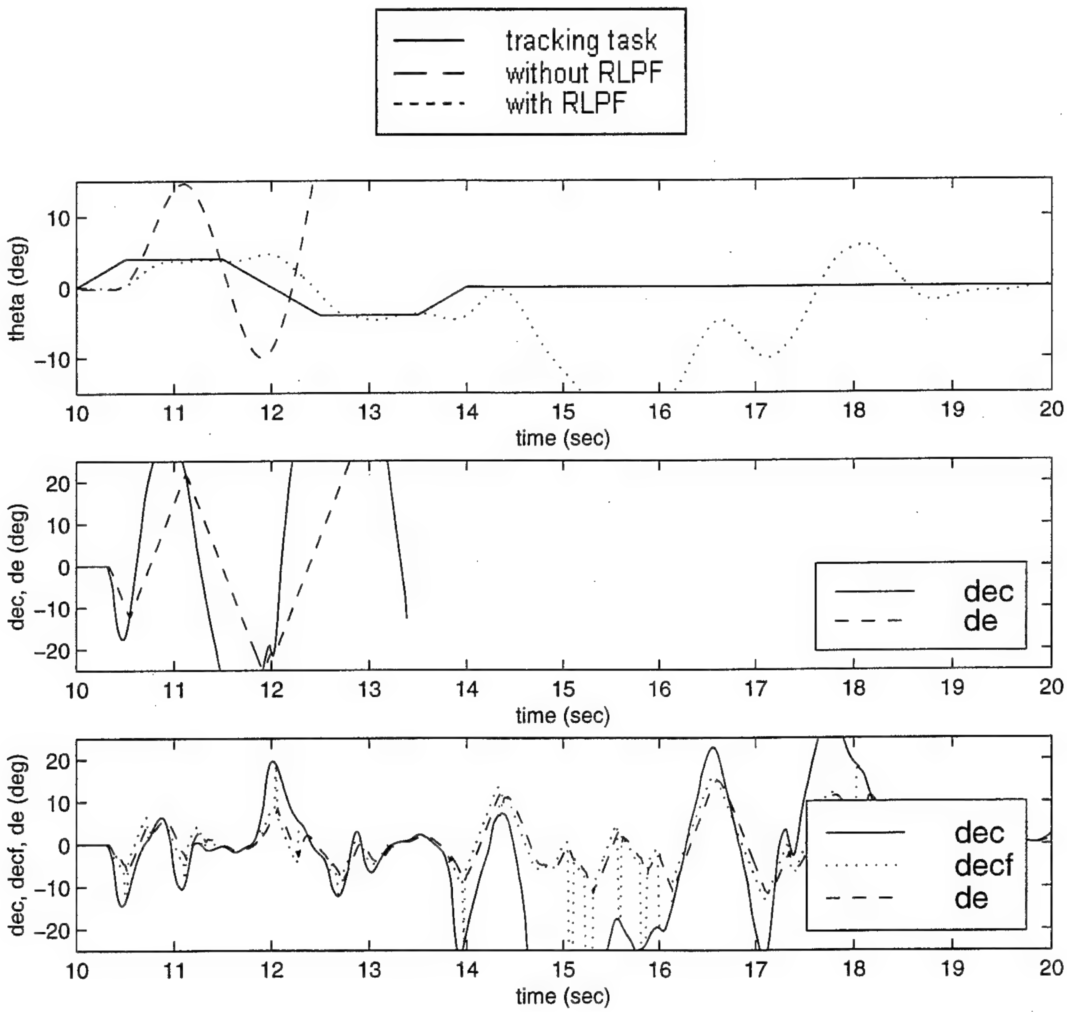


Figure 3-9. 60 deg/sec Actuator Rate Limit (LAMARS)

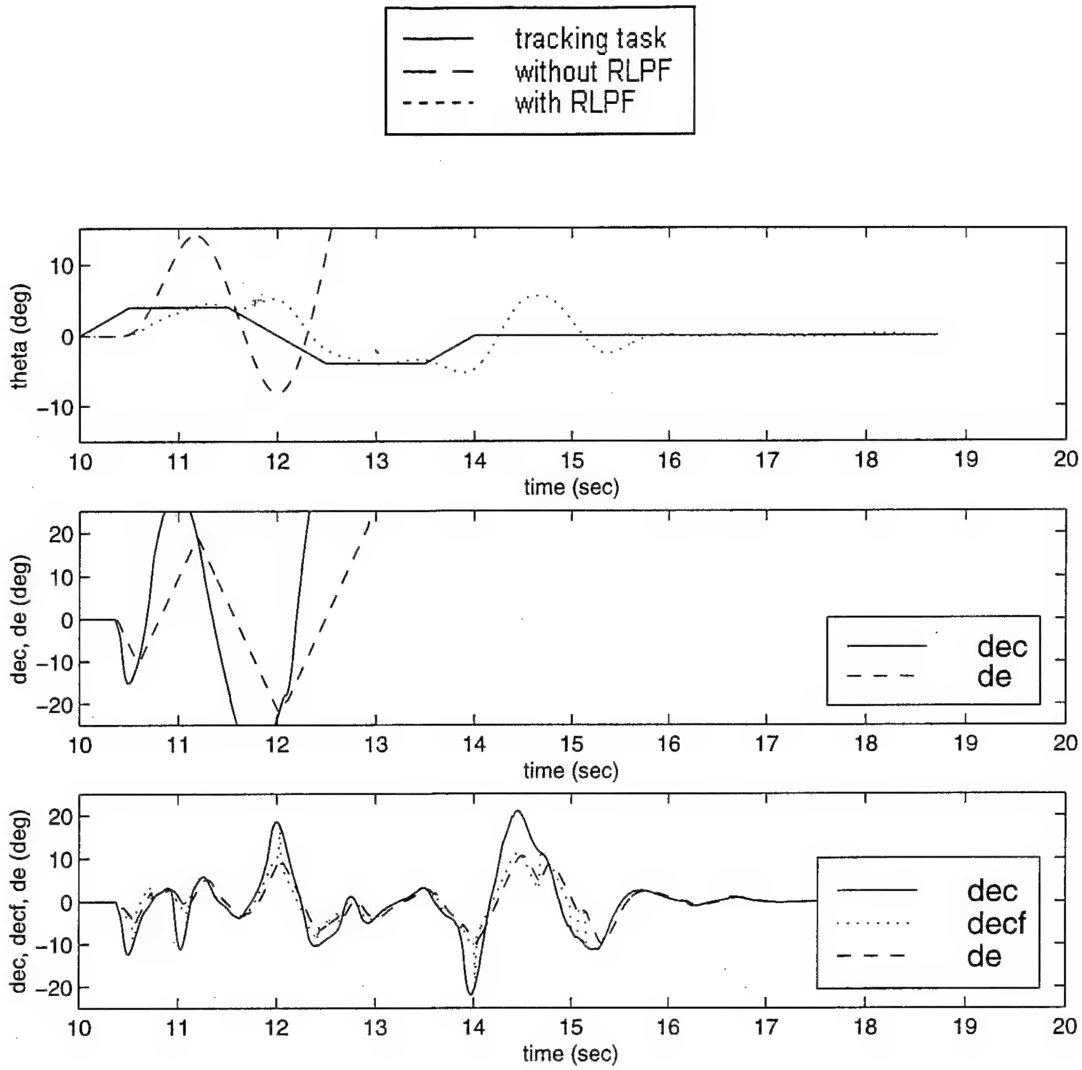


Figure 3-10. 50 deg/sec Actuator Rate Limit (LAMARS)

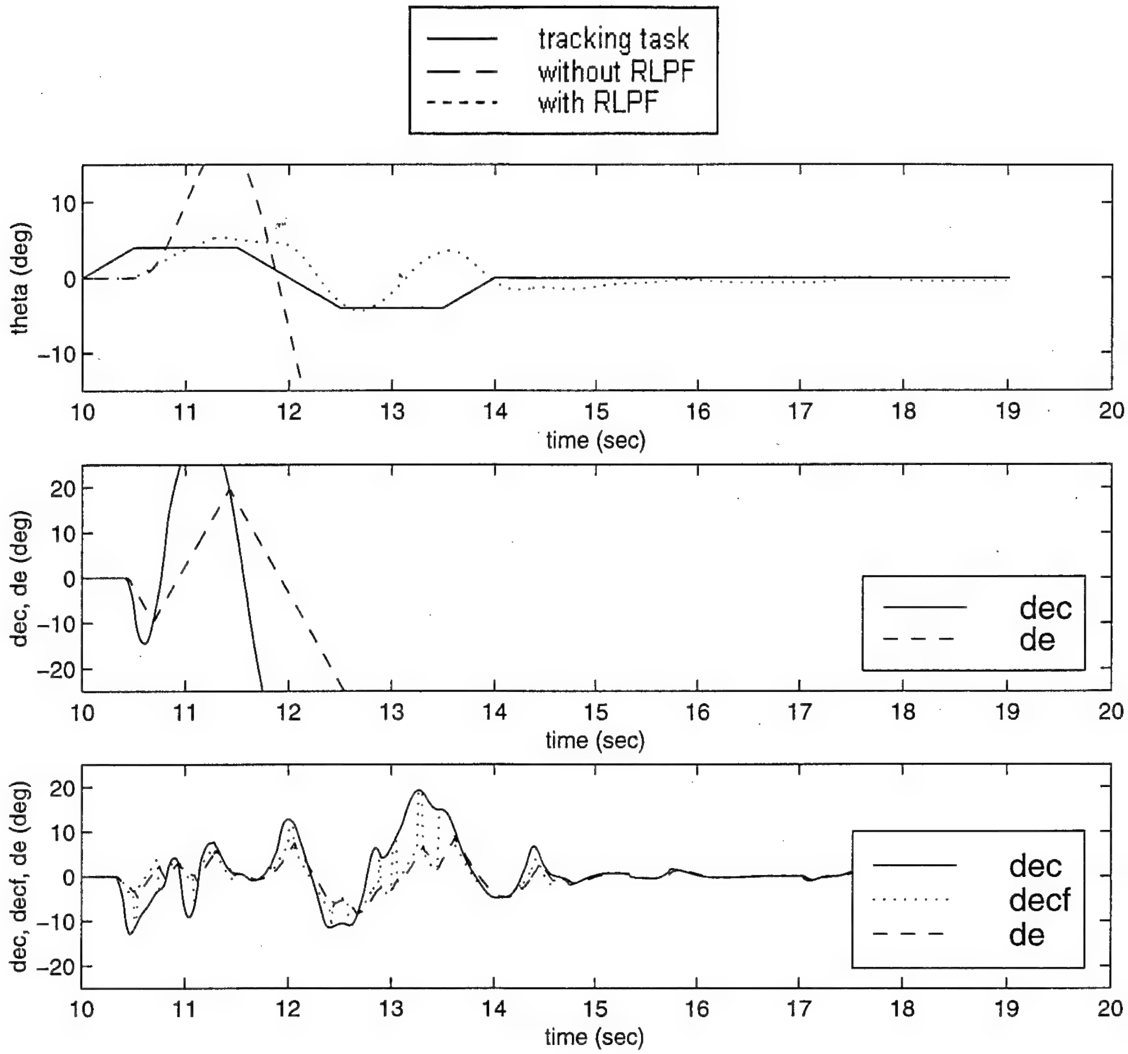


Figure 3-11. 40 deg/sec Actuator Rate Limit (LAMARS)

A LAMARS simulation with 30°/sec rate limiting was accomplished with the RLPF in place and is shown in Figure 3-12. Although the unprotected case was not run at this rate limit, the last three examples clearly demonstrated the unprotected plant could not stay stable here.

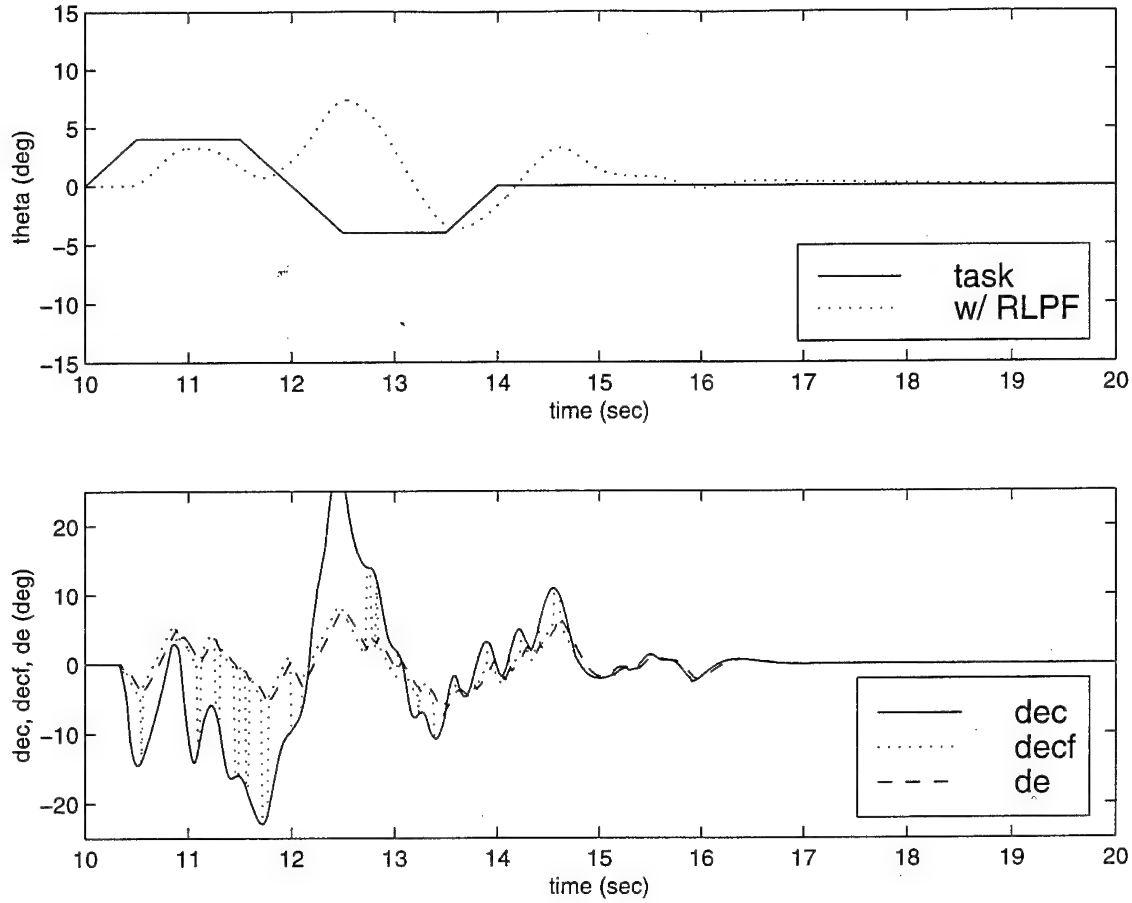


Figure 3-12. 30 deg/sec Actuator Rate Limit (LAMARS)

It should be noted that although the RLPF system remained stable in the above examples, the stick forces were high with low rate limits and satisfactory tracking was intermittent. Handling qualities deficiencies with the RLPF sometimes appeared during aggressive manuevering including apparent uncommanded responses or nonresponsiveness (addressed later during the flight test results). However, the RLPF clearly prevented a catastrophic divergent PIO where not possible without protection.

As a side note, the values of the second derivative and noise filtered second derivative were recorded in the RLPF. For the run depicted in Figure 3-12, the maximum recorded acceleration was $1784°/sec^2$ and, when noise filtered, measured $794°/sec^2$, while

the threshold was $200^{o}/sec^{2}$. The next chapter discusses the simulation results using a software rate limit with and without the RLPF on the pilot command rather than using the RLPF inside the feedback path.

As shown in Figure 3-9, the human pilot departed controlled flight without the RLPF with a 60 deg/sec rate limit on the actuator. The human pilot was able to track with the RLPF down to the lowest rate limit accomplished in LAMARS, 30 deg/sec, as shown in Figure 3-12. Recall from the 64 Hz digital computer simulation summary in Table 3-4 the unprotected Modified Neal-Smith pilot model departed with rate limits below 50 deg/sec and the RLPF protected pilot model departed below 30 deg/sec. The RLPF threshold was at 50 deg/sec^2 in SIMULINK™ and 200 deg/sec^2 in LAMARS and noise levels were different. The validity of using the Modified Neal-Smith pilot model will be addressed further in chapters 4 through 6.

IV. Pilot Command Path Actuator Rate Limit Protection Simulation Results

In this chapter, computer simulation pilot command path protection results are presented first followed by LAMARS results. Flight test recommendations are then made.

Computer Simulation Results

The results in this section are for the 2DU system with a 60°/sec rate limited actuator running at 64 Hz and a 10x integration speed (Figure 2-12 plus digital effects). A larger doublet (±5°) tracking task was used. This doublet case was run in SIMULINK™ (results not shown here) using inner loop RLPF protection as in the previous chapter, but inner loop protection could not prevent instability. However, by removing the RLPF from the inner loop and adding a SWRL with and without the RLPF on the pilot command, departure could be prevented.

Different values of software rate limiting the pilot command are presented with an upper and lower figure for each case (see Figure 4-1 through Figure 4-4). The upper figure is the tracking response. The lower figure is a group of plots where the first column represents the SWRL with and without the RLPF input-output and the second column shows the actuator response. The first row is for the unprotected case, the second row is for the software rate limiter (SWRL) protection scheme (sw), and the third row is for the RLPF plus software rate limiter protection setup (RLPF/sw).

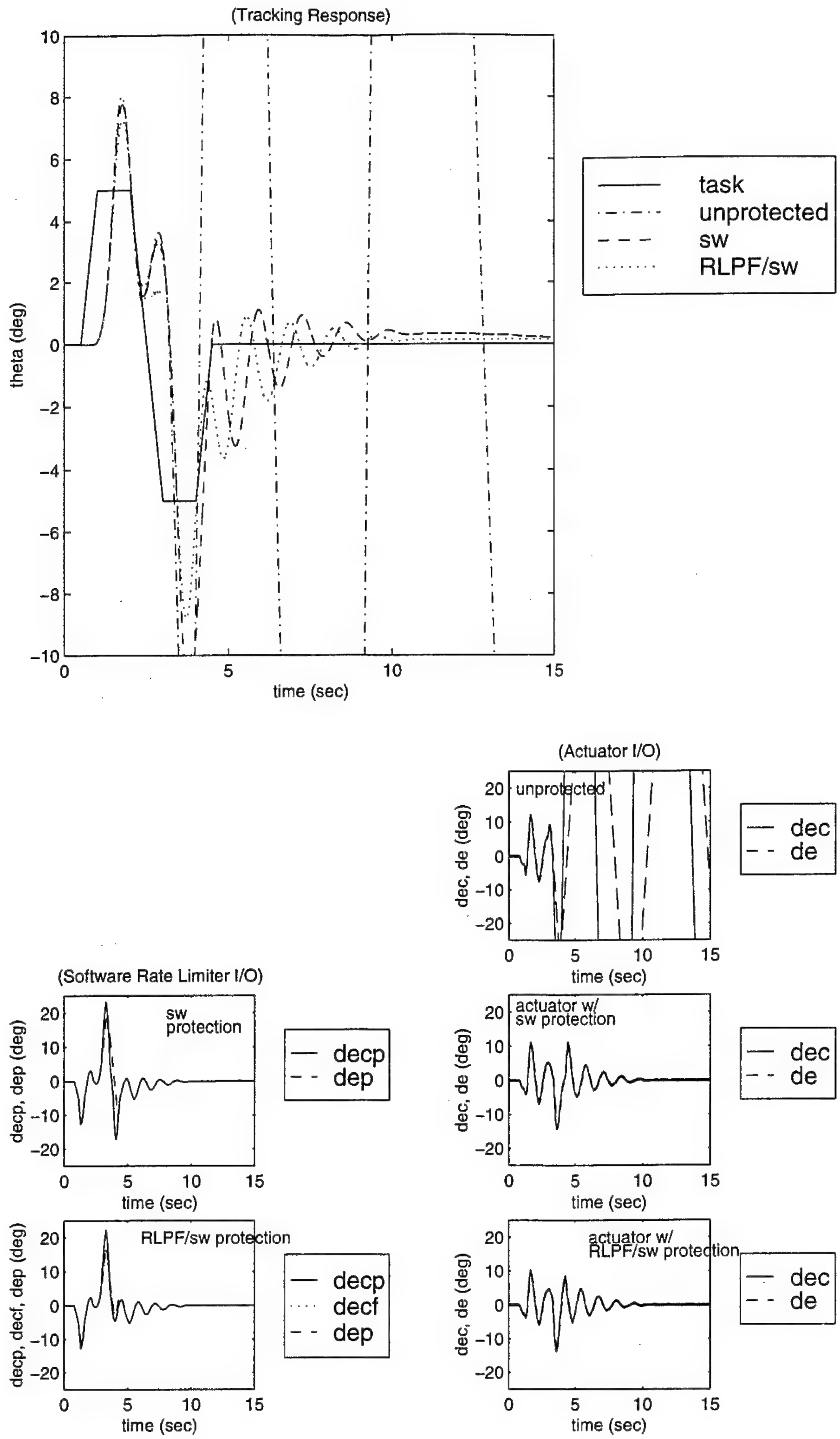


Figure 4-1. 35 deg/sec Software Rate Limit (SIMULINK™)

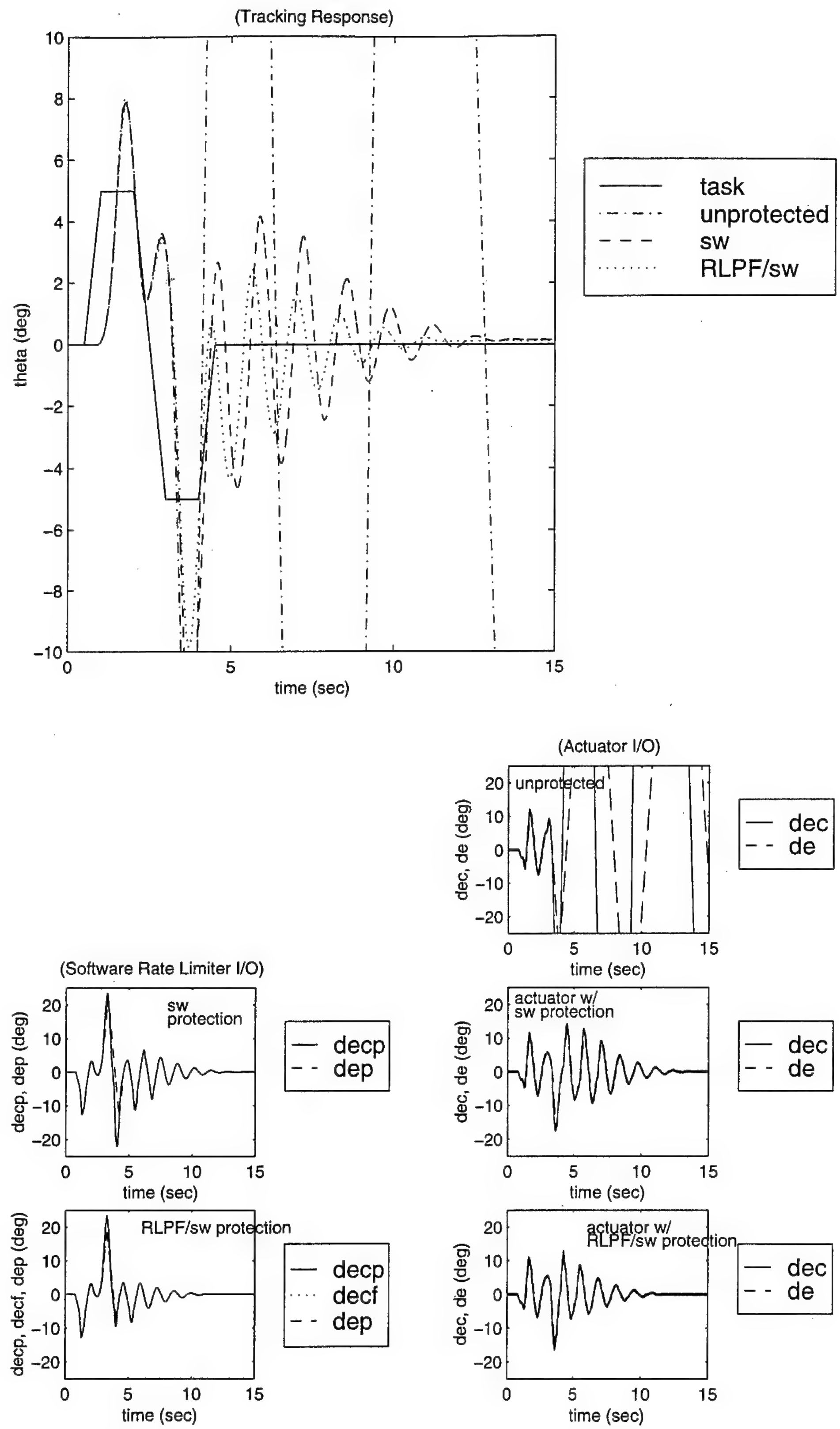


Figure 4-2. 40 deg/sec Software Rate Limit (SIMULINK™)

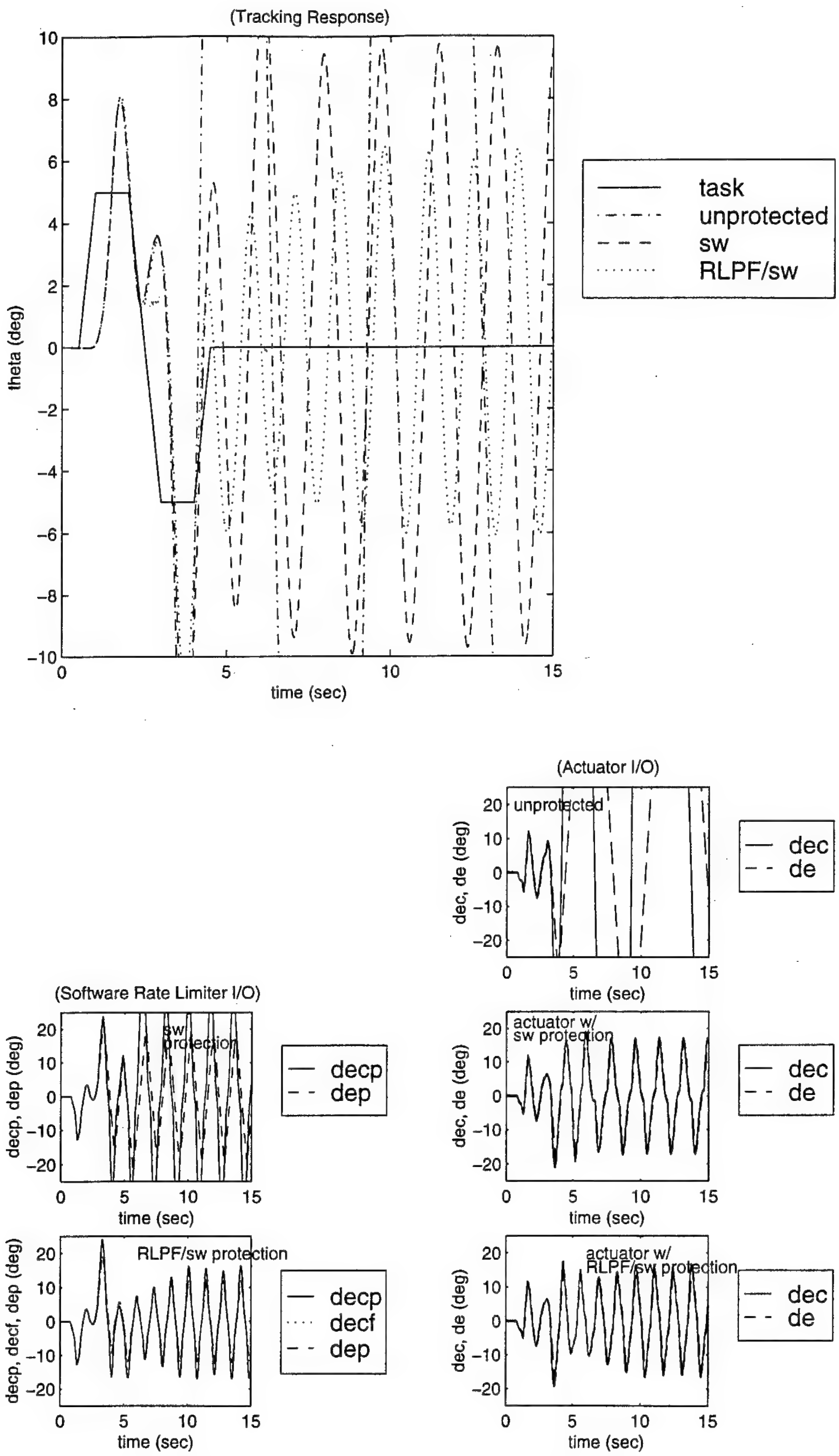


Figure 4-4. 45 deg/sec Software Rate Limit (SIMULINK™)

As seen in the previous cases, when the software rate limit was set very low (35°/sec) departure was avoided, but the question arises if more performance can be squeezed out of the system. At 40°/sec, the SWRL began to rate limit requiring more pilot inputs to dampen than the RLPF plus SWRL combination. By 42.5°/sec, the SWRL was insufficient for this input and the pilot's stick input was clearly rate limiting leading to a limit cycle PIO. The RLPF plus SWRL at 42.5°/sec, however, enabled in-phase reversals and the pilot tracked well. But, at 45°/sec even the RLPF plus SWRL combination was insufficient at preventing a limit cycle PIO. The RLPF reduced the amplitude of oscillation by about 50% over the SWRL alone, but slightly increased the frequency of oscillation.

Although almost all cases simulated showed improvement with the RLPF, a larger task amplitude case where the RLPF caused the pilot to get stuck in a limit cycle PIO is shown in Figure 4-5. In this rare example, the SWRL only configuration actually recovered.

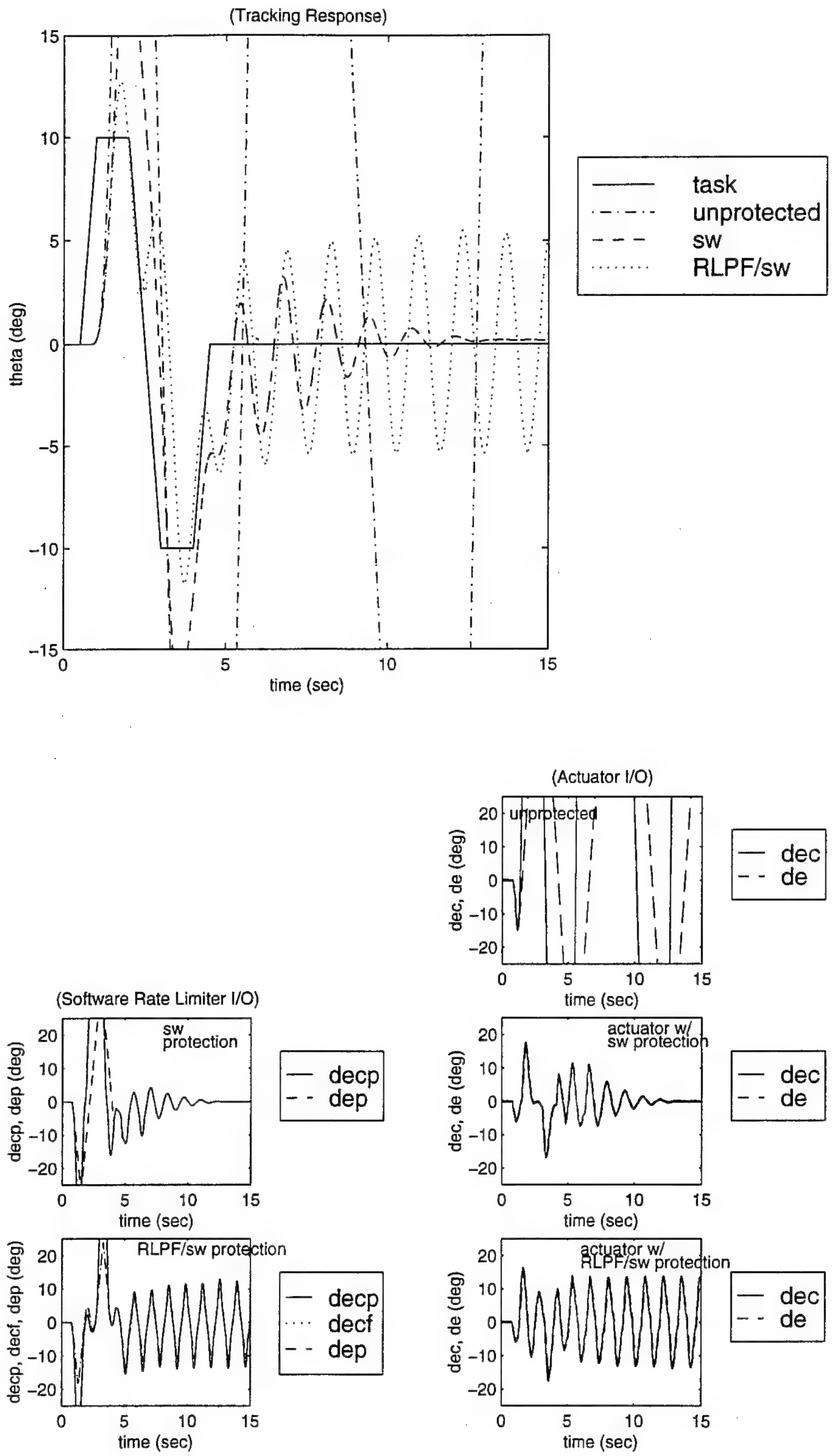


Figure 4-5. 40 deg/sec Software Rate Limit w/Large Doublet (SIMULINK™)

LAMARS Results

The author plus another pilot, Capt Barry St. Germain, flew pilot command path protection tests in the LAMARS simulator. Capt St. Germain is a senior USAF pilot with over 2000 hours in the T-38 and the C-5, but no experience with HUD aircraft. With only two pilots to draw upon for the LAMARS simulation, both extremes of HUD experience were tested. As in the inner loop protection simulator runs, the pilots were kept blind to the specifics and audio plus video were recorded.

For the pilot command path protection configurations, the pilot desired much higher acceleration thresholding. Threshold values around $1000^{\circ}/sec^2$ were determined to be the sweet spot for the author, but Capt St. Germain seemed to prefer a higher value like $1250^{\circ}/sec^2$. Again, high values resulted in a "loose" response and low values resulted in a "sluggish" response. It is interesting the SIMULINK™ Neal-Smith pilot performed better with a lower threshold setting but stick force analysis/pilot comments were not accomplished/available there.

All LAMARS runs were at 64 Hz and the actuator was at a fixed $60^{\circ}/sec$ rate limit while the software rate limit was varied. As shown in chapter three, without any protection the unprotected plant diverged promptly. Therefore, only the results of SWRL protection with and without the RLPF will be presented. The following figures have several plots like those shown previously in this chapter. The tracking response (*sw* for SWRL case and *sw/RLPF* for the case with the RLPF plus SWRL) is the top plot, while the SWRL and the actuator responses are shown in the second row. The RLPF plus SWRL and the corresponding actuator responses are shown in the third row. The author,

pilot A, or Capt St. Germain, pilot B, is also depicted as well as the acceleration threshold (posted on top of the tracking plot). The first case (Figure 4-6) is for the 30°/sec software rate limited case with subsequent figures showing other SWRL values.

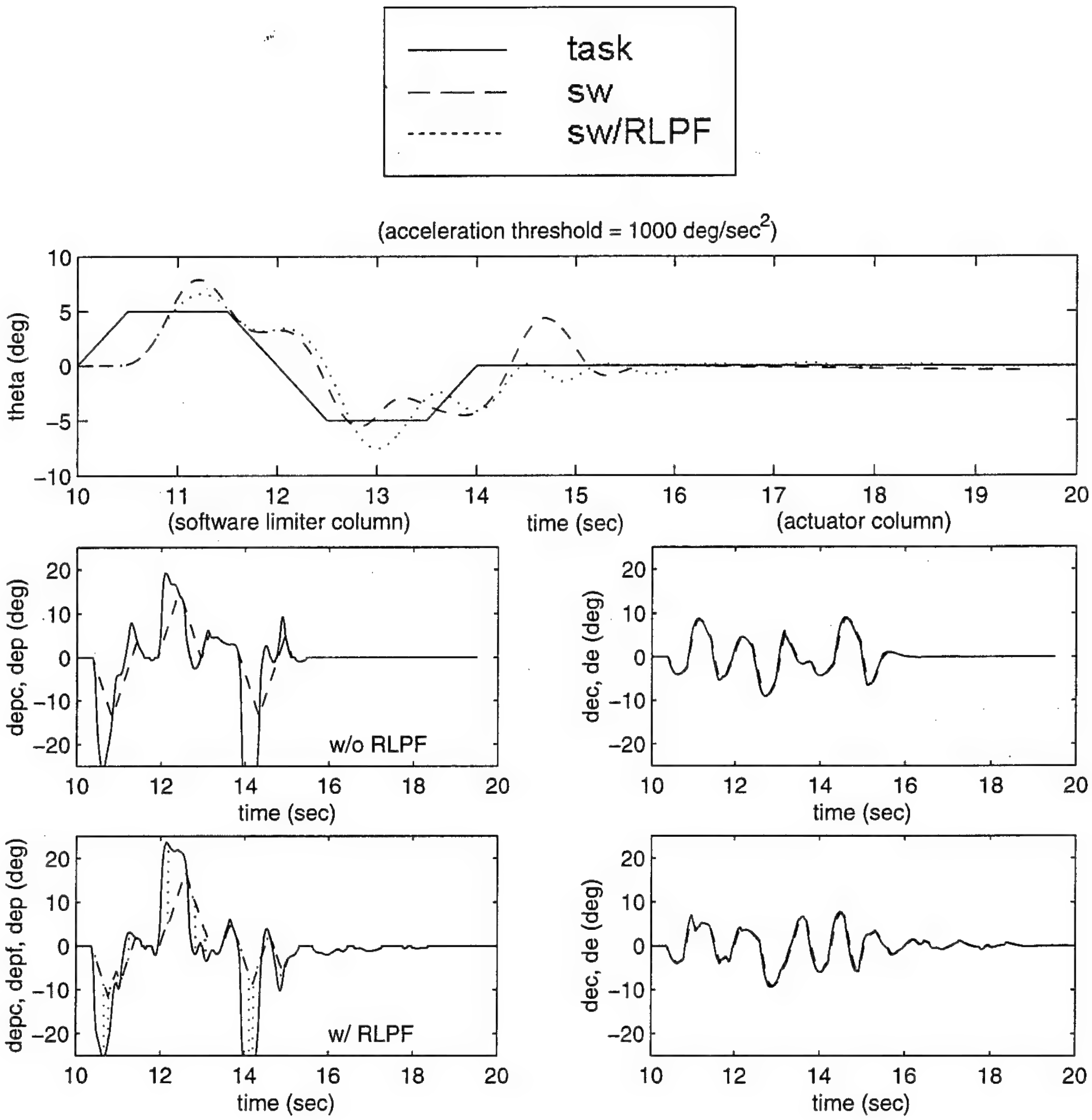


Figure 4-6. Pilot A 30 deg/sec Software Rate Limit (LAMARS)

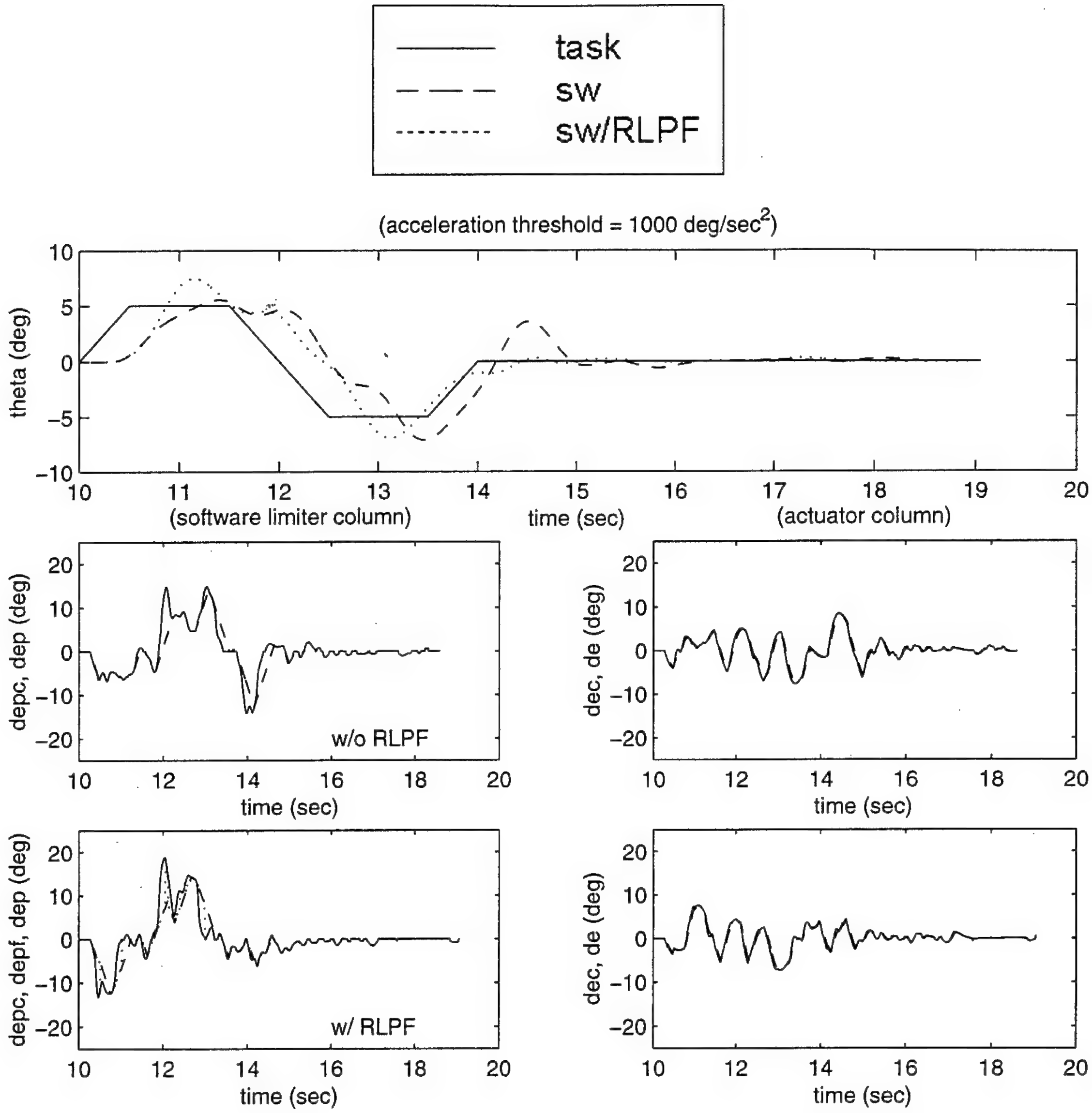


Figure 4-7. Pilot B 30 deg/sec Software Rate Limit (LAMARS)

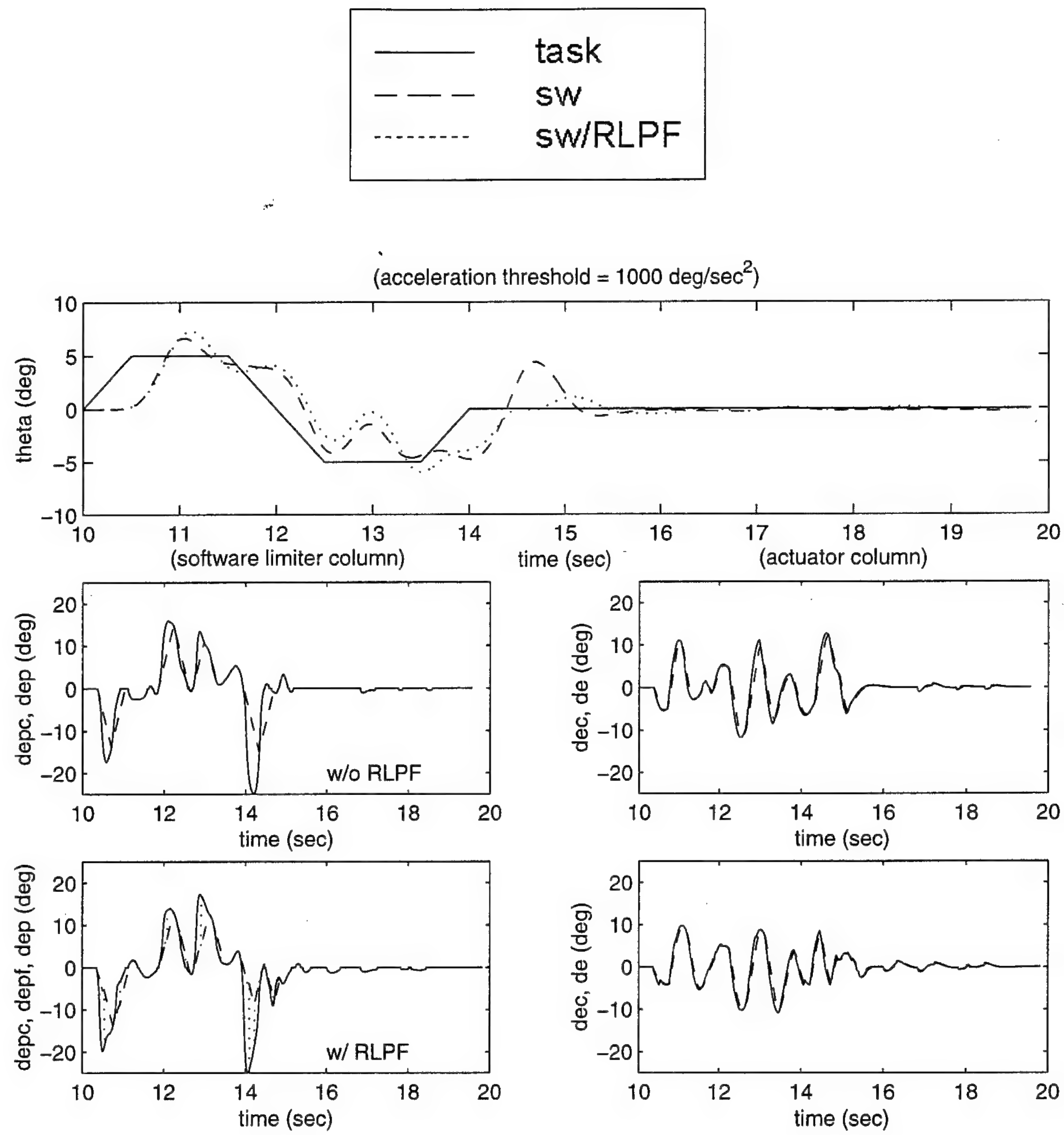


Figure 4-8. Pilot A 40 deg/sec Software Rate Limit (LAMARS)

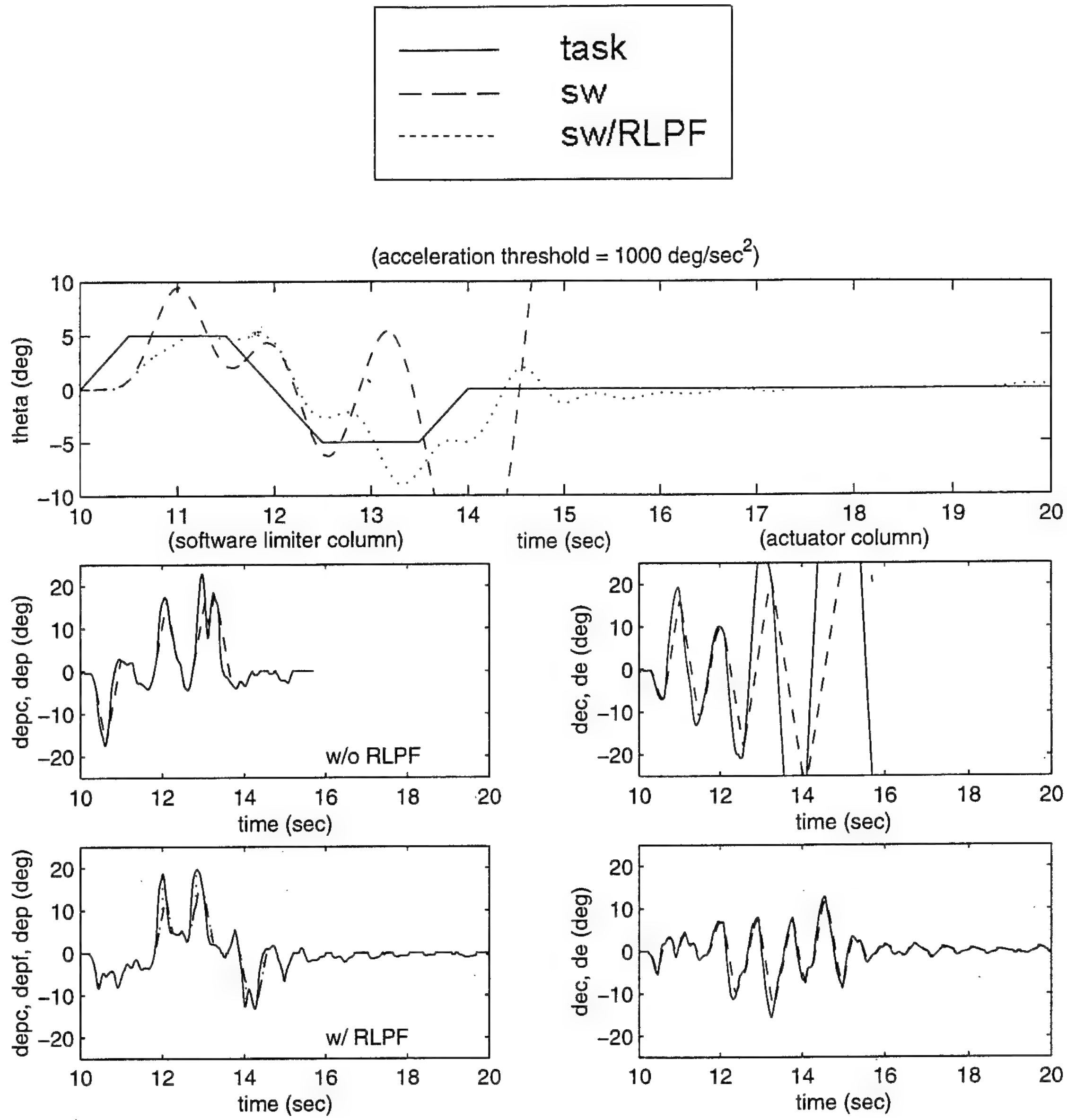


Figure 4-9. Pilot B 55 deg/sec Software Rate Limit (LAMARS)

Results using a lower acceleration threshold are depicted in Figure 4-10. The pilot's performance should be similar for the identically repeated SWRL only configuration in Figure 4-9 and Figure 4-10. The different results show that a human pilot does not repeat tasks identically every time.

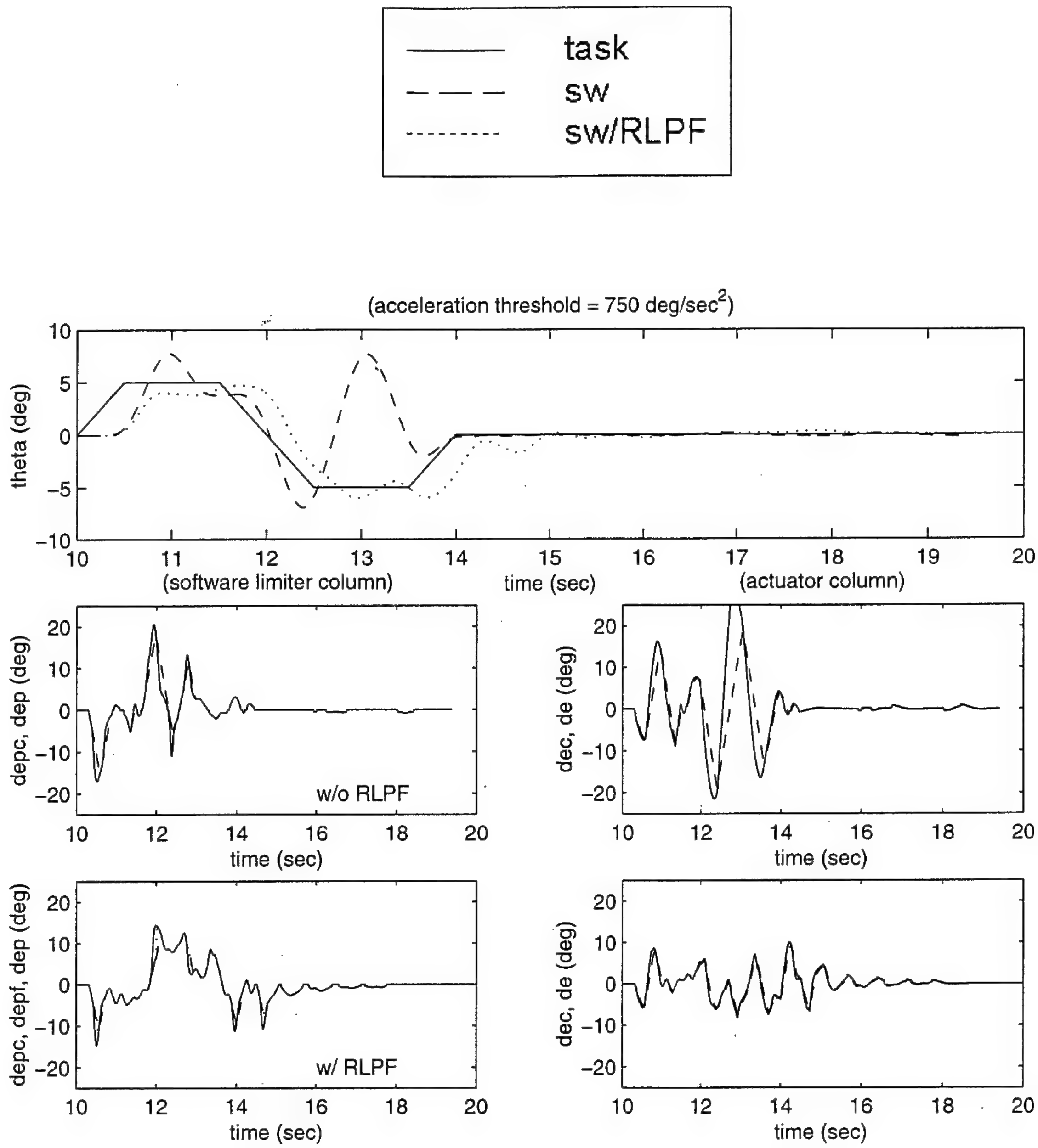


Figure 4-10. Pilot B 55 deg/sec Software Rate Limit #2 (LAMARS)

A slightly different and extended tracking task is depicted in Figure 4-11:

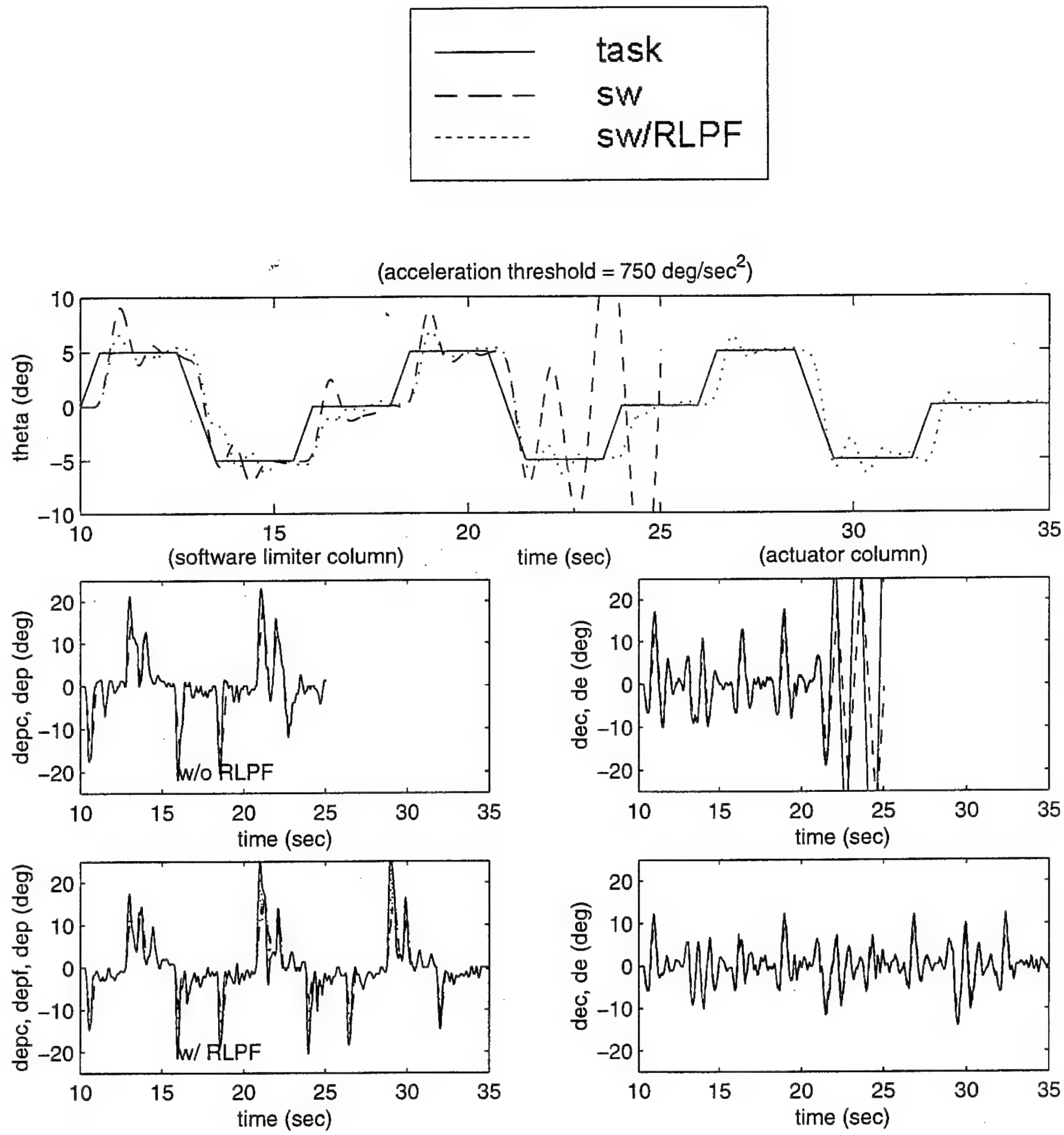


Figure 4-11. Pilot B 50 deg/sec Software Rate Limit (LAMARS)

Of note, the noise filtered value for acceleration recorded inside the RLPF infrequently exceeded the threshold. The unfiltered acceleration value was often higher than the threshold, but using non-noise filtered acceleration would cause ratcheting in the switching logic. Additionally, LAMARS had no artificial noise injected into the loop and analysis done on the stick inputs revealed stick noise to have an RMS value on the order of 10^{-6} degrees. Data from previous flight test aircraft have shown much higher values of noise. This is addressed further in chapters 5 and 6.

One problem with setting the acceleration threshold low (aside from pilot complaints of heavy stick forces) is the RLPF stays on a lot and can lead to large biases in the filter. On certain occasions this large bias may actually lead to a situation where the pilot is commanding the actuator in one direction, but the biased RLPF output is actually commanding the opposite direction. This leads the pilot to believe his input was not accepted and he will put in another input. This is frustrating and leads to over-controlling. This was noted during flight test and is addressed in chapters 5 and 6. An example of this is shown in Figure 4-12 where the threshold was set to $500^{\circ}/sec^2$. Pay close attention around 14-15 seconds where the pilot interpreted a lack of response and made a second input. This resulted in poor tracking.

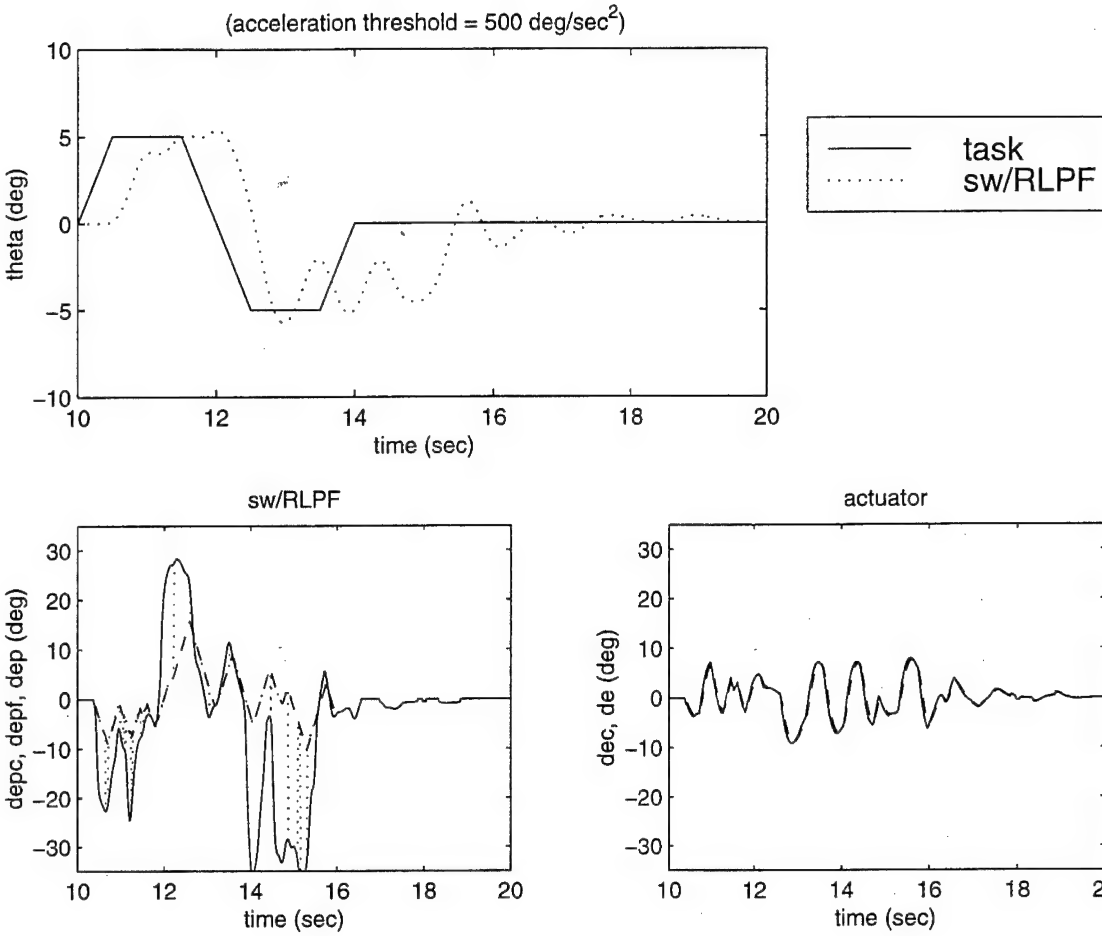


Figure 4-12. Pilot A 30 deg/sec Software Rate Limit (LAMARS)

Previously shown in this chapter the Modified Neal-Smith pilot required a SWRL setting below 42.5 deg/sec to prevent instability in the SWRL only configuration. For the RLPF plus SWRL configuration with an RLPF threshold of 50 deg/sec^2, the Modified Neal-Smith pilot required a SWRL setting below 45 deg/sec^2. High stick forces in LAMARS required raising the RLPF threshold to 750+ deg/sec^2. Human pilot B

required SWRL settings below 50 deg/sec at times to prevent departure for the SWRL only configuration. Neither human pilot A nor B experienced departure with the RLPF plus SWRL configuration in LAMARS. The computer results did not closely correlate with LAMARS. Using a longer task and the same acceleration threshold, flight test data will be compared to computer simulation in chapters 5 and 6.

Analysis and Flight Test Desires

Based on the SIMULINK™ and LAMARS results, the RLPF could be used in both inner loop or pilot command path protection configurations. The primary question raised in LAMARS was the effect of acceleration thresholding on stick forces based on RLPF placement.

In the inner loop configuration the RLPF prevented divergent PIO in SIMULINK™ to a point, and in LAMARS prevented divergent PIO on all cases run. As the actuator rate limit was lowered in LAMARS, the pilot suffered from a lack of pitch response resulting in poor tracking, but no divergent PIO.

In the pilot command path protection configuration, the RLPF plus SWRL generally resulted in lower track error compared to the SWRL alone. When the SWRL was set high pushing for more performance, the RLPF plus SWRL prevented a divergent PIO on several occasions where the SWRL alone diverged. On no occasion in LAMARS did the RLPF plus SWRL combination diverge.

For flight test, the sponsor (AFRL) desired only testing the pilot command path protection configurations. They also wanted to test a predicted Level 1 aircraft and Level 2 aircraft with identically unstable inner loops (similar to the 2DU configuration shown

previously on the NT-33). Additionally, they desired a pitch and roll tracking task similar to the one flown during HAVE LIMITS. Flight preparation and simulation for flight test are presented in Chapter 5. Results from flight test are shown in Chapter 6.

V. Flight Test Preparation

Pre-Flight Test Development

The pilot command path protection configurations were tested during the HAVE FILTER flight test project (Chapa and others, 1998). Testing was performed at the Calspan flight research facility in Buffalo, NY, by a team of USAF Test Pilot School (USAF TPS) students. Thirteen test flights were flown 1 through 18 September 1998, accumulating 14.9 hours of flying time.

Some work was accomplished under USAF TPS Job Order Number M96J0200. The responsible test organization (RTO) was the Air Force Research Laboratory, Wright-Patterson AFB, Ohio. The USAF TPS test team was a participating test organization (PTO). Four calibration/validation flights and nine test flights were flown in support of this project.

Flight Test Overview

The HAVE FILTER test program used the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) to simulate two highly augmented fighter aircraft with identical unstable inner loops. When not under rate limiting conditions, pitch rate (q) and angle-of-attack (α) feedbacks resulted in two different sets of aircraft dynamics. Using MIL-STD 1797A Control Anticipation Parameter (CAP) criteria (DoD, 1990), one of these, highly augmented fighter aircraft #1, or HAFA 1, was predicted to have Level 1

handling qualities for a fighter tracking task. The other, HAFA 2, was predicted to have Level 3 handling qualities for the same task.

The flight test was accomplished using a buildup approach. Phase 1 (semi-closed loop handling qualities) tasks were followed by Phase 2 (high bandwidth handling qualities during tracking (HQDT)) using a pitch axis only flight test heads-up display (HUD) tracking task. The HQDT piloting technique was defined as: "Track a precision aim point as aggressively and assiduously as possible, always striving to correct even the smallest of tracking errors" (USAF TPS, 1998).

These maneuvers were followed by a Phase 3 (operational tracking) task. During the Phase 3 task, the pilot attempted to track a multi-axis maneuvering HUD target, minimizing error throughout the task. Although during Phase 3 the HUD target moved in both the pitch and roll axes, the primary emphasis was pitch tracking.

Comparisons between the baseline aircraft, the baseline plus SWRL, and the baseline plus RLPF plus SWRL combination were made. Critical data included pilot comments, PIO tendency ratings for the Phase 2 and 3 tasks, and Cooper-Harper ratings for the Phase 3 task.

Simulation for Flight Test

SIMULINK™ simulations were accomplished using the NT-33 2DU configuration previously studied (the VISTA model was not available early enough before flight test). However, the simulated first order rate limited actuator (not the NT-33 actuator) in Figure 2-6 was replaced with a second order rate limited actuator model described as follows:

$$\frac{\delta_e}{\delta_{e_c}} = \frac{60^2}{[0.7,60]}$$

This was implemented into the SIMULINK™ structure in Figure 5-1:

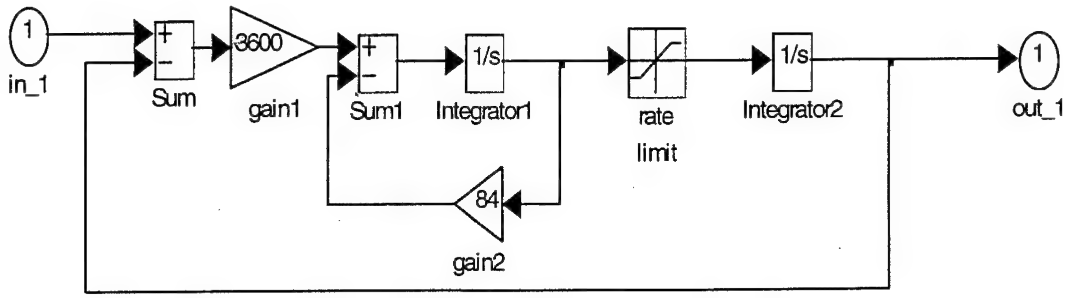


Figure 5-1. Second Order Rate Limited Actuator Model

Simulation was used to determine the optimal tracking task gain. An optimized tracking task was one that had large enough pitch changes to cause departure on the baseline aircraft configurations at some point in the profile without causing nuisance safety trips. Safety trips terminate in-flight simulation and revert back to the host aircraft control laws in the event of computing errors or to prevent structural damage or to prevent departure from controlled flight. Computer simulation of the HAFA 1 aircraft was accomplished using various software rate limits and pre-filter acceleration thresholds.

The simulations were performed using the following time truncated pitch only tracking task defined in MIL-STD 1797A:

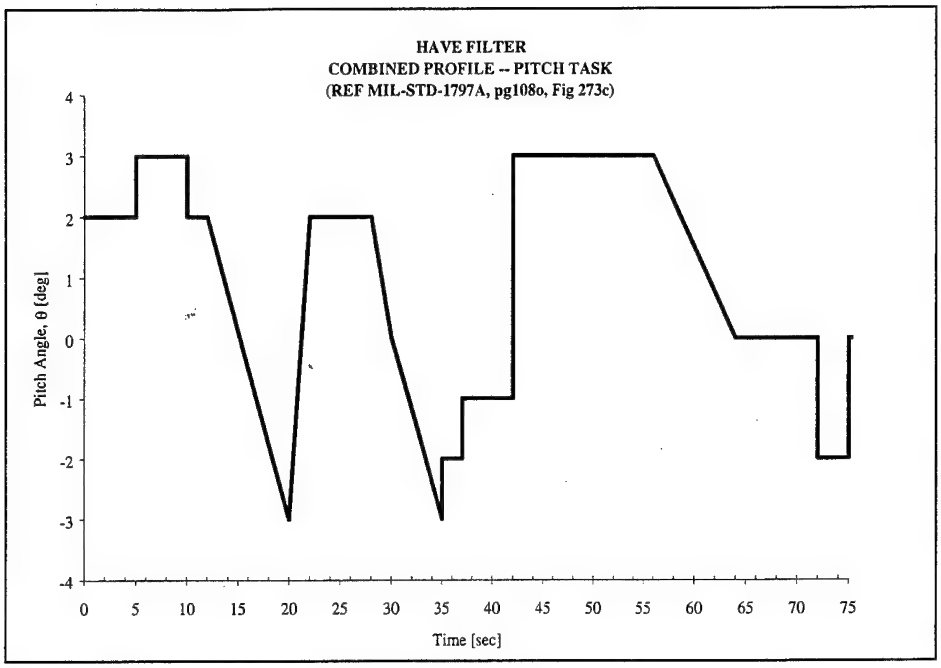


Figure 5-2. HUD Pitch Only Tracking Task

This task was the baseline task for simulation. A gain was placed in front of the task to vary the amplitude in search of the optimal task—one that provided departure for the unprotected configuration at some point in the task (departure expected during large steps or rapidly changing pitch directions) but not during benign maneuvering portions of the task. With over 100 safety trips in the VISTA, it was deemed imprudent to simulate all trips. With Calspan's advice, alpha and n_z trips were chosen for simulation verification. The alpha trip boundary was –10 deg to +16 deg and the n_z trip boundaries were –2 g to +6.5 g. The baseline task was as shown in Figure 5-2 with the gain being 1, 1.5, 2 (doubling the task amplitude), or 3 (tripling the task amplitude) for simulation.

Calspan provided time histories of stick noise for the VISTA that showed very low noise levels with a mean value of approximately 10^{-3} inches in both pitch and roll. Stick gains were on the order of 20 deg/in resulting in noise on the order of 0.02 deg command

stabilator. Since noise proved to be harmful in previous pre-filter attempts, a much higher noise baseline level of 0.1° commanded elevator was simulated. From this baseline, additional noise levels of zero and 0.2° were used for a more thorough evaluation. An important change for this simulation and subsequent flight test was the removal of the second noise filter in the RLPF (see Figure 2-10) after the second derivative based on lower expected noise levels. This will improve filter performance and modern aircraft can be expected to have noise levels similar to the VISTA NF-16D. The RLPF used for flight test is shown in Figure 5-3.

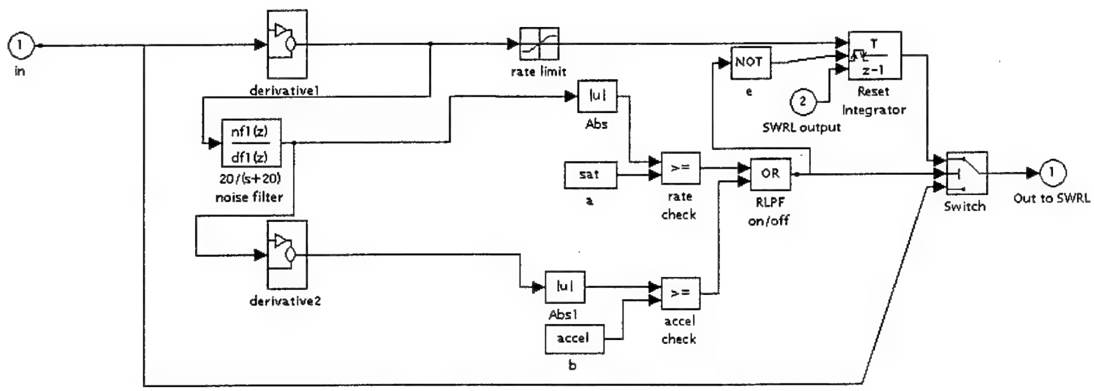


Figure 5-3. Flight Test RLPF Configuration

Simulation of the baseline task for the unprotected aircraft with Ktask=1 resulted in no departure regardless of noise (0, 0.1, or 0.2 deg δ_{ec}) value. At all other task gains, (Ktask=1.5, 2, and 3), the baseline departed for all noise values.

SWRL only simulation results are shown in Table 5-1 for different levels of noise and task amplitude gain (Ktask) with SWRL settings from 20-55 deg/sec in 5°/sec intervals. The SWRL value required to prevent departure is depicted.

Table 5-1. SWRL Simulation Stability Requirements

Noise RMS, δ_{en} (deg δ_{ec})	Task Gain (Ktask)	SWRL Required for Stability (deg/sec)
0, 0.1, and 0.2	1.5	30
	2	35
	3	30

For the RLPF plus SWRL simulations, the SWRL settings were again varied from 20 deg/sec to 55 deg/sec in 5 deg/sec intervals. Stick acceleration threshold settings were varied from 100 deg/sec^2 to 1100 deg/sec^2 in 200 deg/sec^2 intervals. RLPF effects on departure susceptibility are shown in Table 5-2 through Table 5-10. The differences from one table to another are the noise level (δ_{en}) and/or task amplitude gain (Ktask). A shaded "D" indicates departure at that point in the matrix and an unshaded "N" indicates no departure. As an aid for comparing with the SWRL only results just presented, those SWRL only settings resulting in departure are lightly shaded on the left side of the table.

Table 5-2. RLPF Simulation Effects, $\delta_{en} = 0$ deg, Ktask = 1.5

SWRL (deg/sec)	100	RLPF 300	Acceleration 500	Threshold 700	Setting 900	(deg/sec^2) 1100
55	N	D	D	D	D	D
50	N	D	D	D	D	D
45	D	D	D	D	D	D
40	D	D	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-3. RLPF Simulation Effects, $\delta_{en} = 0$ deg, Ktask = 2

SWRL (deg/sec)	100	RLPF 300	Acceleration 500	Threshold 700	Setting 900	(deg/sec^2) 1100
55	D	D	D	D	D	D
50	D	D	D	D	D	D
45	D	D	D	D	D	D
40	N	D	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-4. RLPF Simulation Effects, $\delta_{en} = 0$ deg, Ktask = 3

SWRL (deg/sec)	100	RLPF 300	Acceleration 500	Threshold 700	Setting 900	(deg/sec^2) 1100
55	D	D	D	D	D	D
50	D	D	D	D	D	D
45	D	D	D	D	D	D
40	D	D	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-5. RLPF Simulation Effects, δ_{en} = 0.1 deg, Ktask = 1.5

SWRL (deg/sec)	RLPF Acceleration Threshold Setting (deg/sec²) 100	300	500	700	900	1100
55	N	D	D	D	D	D
50	N	D	D	D	D	D
45	N	D	D	D	D	D
40	N	D	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-6. RLPF Simulation Effects, δ_{en} = 0.1 deg, Ktask = 2

SWRL (deg/sec)	RLPF Acceleration Threshold Setting (deg/sec²) 100	300	500	700	900	1100
55	D	D	D	D	D	D
50	D	D	D	D	D	D
45	N	D	D	D	D	D
40	N	D	D	D	D	D
35	N	N	D	D	D	D
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-7. RLPF Simulation Effects, δ_{en} = 0.1 deg, Ktask = 3

SWRL (deg/sec)	RLPF Acceleration Threshold Setting (deg/sec²) 100	300	500	700	900	1100
55	D	D	D	D	D	D
50	D	D	D	D	D	D
45	D	D	D	D	D	D
40	N	D	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-8. RLPF Simulation Effects, δ_{en} = 0.2 deg, Ktask = 1.5

SWRL	RLPF Acceleration Threshold Setting (deg/sec^2)					
(deg/sec)	100	300	500	700	900	1100
55	N	D	D	D	D	D
50	N	D	D	D	D	D
45	N	N	D	D	D	D
40	N	N	D	D	D	D
35	N	N	N	N	N	N
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-9. RLPF Simulation Effects, δ_{en} =0.2 deg, Ktask = 2

SWRL	RLPF Acceleration Threshold Setting (deg/sec^2)					
(deg/sec)	100	300	500	700	900	1100
55	N	D	D	D	D	D
50	D	N	D	D	D	D
45	N	N	D	D	D	D
40	N	N	D	D	D	D
35	N	N	D	D	D	D
30	N	N	N	N	N	N
25	N	N	N	N	N	N
20	N	N	N	N	N	N

Table 5-10. RLPF Simulation Effects, δ_{en} =0.2 deg, Ktask = 3

SWRL	RLPF Acceleration Threshold Setting (deg/sec^2)					
(deg/sec)	100	300	500	700	900	1100
55	D	D	D	D	D	D
50	D	D	D	D	D	D
45	D	D	D	D	D	D
40	N	D	D	D	D	D
35	D	D	D	D	D	D
30	D	D	D	D	D	D
25	D	D	D	D	D	D
20	D	D	D	D	D	D

As expected, the filter generally worked better with a lower acceleration threshold. During LAMARS simulation, high stick forces were observed with low thresholds. However, high stick forces with low thresholds were absent during flight test on the NF-16D VISTA and a lower threshold setting was used effectively during flight test (explained in chapter 6). The simulation results in this chapter predicted Ktask=1.5 be required during flight test for satisfactory baseline aircraft departure characteristics.

Test Aircraft Implementation

The test item for the HAVE FILTER test program consisted of several components implemented into the VISTA: unstable bare airframe dynamics (pole at s=+1.34 with a time to double amplitude, T_2, of 0.5 seconds), q and α feedbacks generating the HAFA 1 and HAFA 2 overall dynamics (see Appendix B), the SWRL software as implemented into the VISTA, the RLPF as implemented into the VISTA, and finally the stick dynamics (explained later). No artificial noise was injected into the loop.

The NF-16D VISTA stabilator actuators were software rate limited to 60 deg/sec inside the feedback loop to simulate typical modern fighter aircraft and keep the VISTA from rate limiting. The VISTA's actual actuator rate limit was approximately 70 deg/sec at the test condition. Generic flight control diagrams of the baseline (configuration A), baseline plus SWRL (configuration B), and baseline plus RLPF plus SWRL (configuration C) implemented into the VISTA are shown in Figure 5-4 through Figure 5-6.

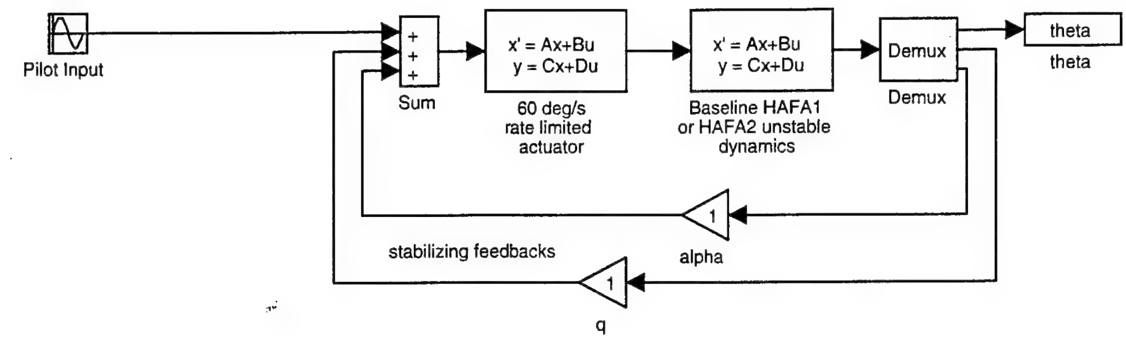


Figure 5-4. Baseline Configuration A

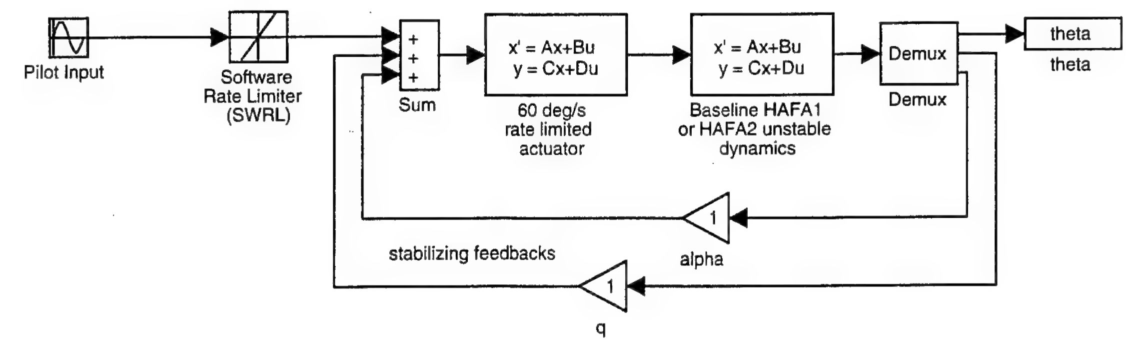


Figure 5-5. SWRL Only Configuration B

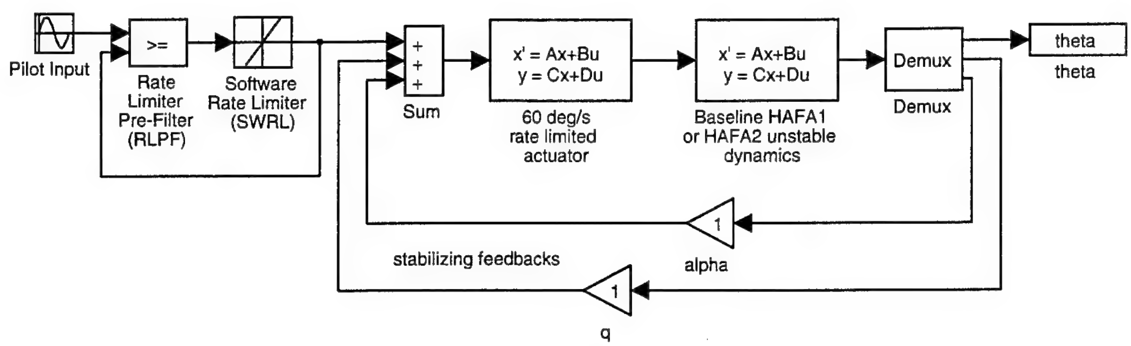


Figure 5-6. RLPF Plus SWRL Configuration C

Flight Test Aircraft

The test aircraft, the USAF NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA), SN 86-0048, is owned by the Air Force Research Laboratory and operated and maintained by Calspan. The VISTA is a highly modified Block 30 Peace

Marble F-16D aircraft with Block 40 avionics powered by an F100-PW-229 engine. The front cockpit included several VSS control panels, a removable variable feel centerstick controller, and a variable feel sidestick controller. The centerstick was desired but broken with insufficient time to fix for this project. Therefore, the sidestick was used. The sidestick controller had a rotation angle of 10.5 deg and stick gains of 20.0 and 5.7 deg of stabilator command per inch of stick deflection for the HAFA 1 and HAFA 2 configurations, respectively. The sidestick properties are shown in Table 5-11.

Table 5-11. HAVE FILTER Sidestick Characteristics

	Pitch	**Roll**
Gradient	51 lb/in	21 lb/in
Fwd / Left	-0.35 in	-0.55 in
Aft / Right	+0.75 in	+0.55 in
Natural Frequency, ω_n	30 rad/sec	30 rad/sec
Damping Ratio, ζ	0.7	0.7

The front cockpit also included a programmable display system (PDS) for the HUD. Most basic aircraft switches and controls were moved to the rear cockpit for the safety pilot. The rear cockpit used conventional F-16 controls except that the throttle was driven by a servo system when the VSS was in use. The primary VSS controls and displays were also located in the rear cockpit. The hydraulic system was enhanced with increased capacity pumps, lines, and high-rate actuators for the flaperons and horizontal tails.

The analog flight controls system was replaced with a modified Block 40 Digital Flight Control System which incorporated the interface for the VSS. The VSS generated signals to operate the flight controls using a virtually unlimited set of command gains that

were changeable in flight. The system consisted of three Hawk computers that generated the commands for the flight controls, a feel system computer that controlled the feel for the front cockpit sidestick, and a Raymond disk that stored preprogrammed sets of gains and control laws for VSS operation. More detailed information can be found in the VISTA Partial Flight Manual (Hutchinson, 1996). The VISTA operational envelope is shown in Figure 5-7.

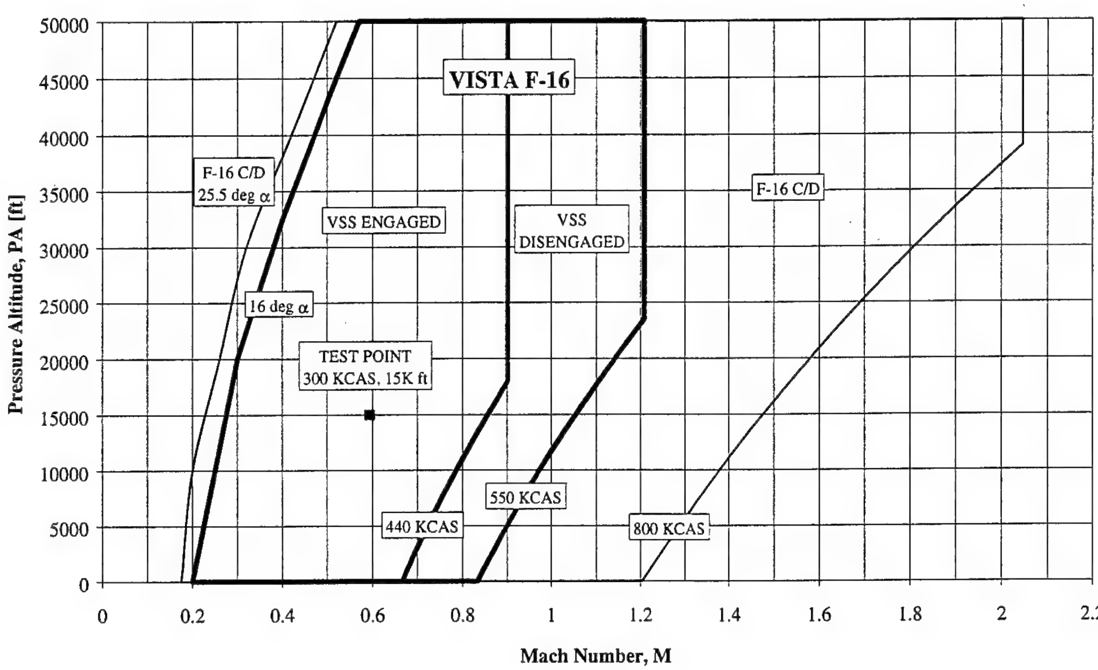


Figure 5-7 VISTA NF-16D Operational Envelope, 1 g

Flight Test Objective

The flight test objective was to evaluate the performance SWRL with and without the RLPF on the pilot command of a highly augmented fighter aircraft under actuator rate limiting during a fighter HUD tracking task. Both HAFA 1 and HAFA 2 aircraft configurations were flown. Verification data for the HAFA 1 and HAFA 2 configurations

are in Appendix B. The flight test objective was met. Specific sub-objectives are shown next.

HAFA 1 and HAFA 2 Handling Qualities (Configuration A).

Determine baseline handling qualities for the HAFA 1 and HAFA 2 aircraft.

Software Rate Limit (SWRL) Evaluation (Configuration B).

Evaluate the protection provided by a SWRL acting on the pilot command. Compare results to the baseline airframe handling qualities for both the HAFA 1 and HAFA 2 aircraft.

Rate Limiter Pre-Filter (RLPF) Plus SWRL Evaluation (Configuration C).

Evaluate the performance of the RLPF plus SWRL on the pilot command. Compare results to the baseline airframe and baseline airframe plus SWRL handling qualities for both the HAFA 1 and HAFA 2 aircraft.

VI. Flight Test

General Information

All testing was conducted at 15,000 feet pressure altitude and 300 knots calibrated airspeed (KCAS). Both the predicted Level 1 aircraft (HAFA 1) and the predicted Level 3 aircraft (HAFA 2) configurations were flown with the following designations:

A) baseline aircraft, B) baseline aircraft plus the SWRL on the pilot command, and

C) baseline aircraft with the RLPF plus SWRL combination on the pilot command.

Each pilot flew the same test points but was blind to the configuration selection throughout the flight test phase of the project. However, the safety pilot (Mr. Jeff Peer of Calspan) knew which test points were being flown and implemented configuration changes in flight. Pilots are identified throughout the report as described in Table 6-1.

Table 6-1. Pilot Designations

Pilot	Designation	Primary Operational Experience	Total Flight Hours
Michael Chapa, Capt, USAF	Pilot A	F-15 / F-16	1,350+
Matthew LeTourneau, Lt Cmdr, USN	Pilot B	F-14	1,500+
Terry Parker, Flt Lt, RAF	Pilot C	AV-8	2,000+

Ground testing was accomplished prior to the calibration and test flights. Ground testing verified proper implementation of the test matrix and proper operation of the VSS and HUD tracking tasks.

Limitations

The primary limitation on this project stemmed from VISTA safety trips. As previously discussed, the VISTA was equipped with over 100 safety trips. Since one of the primary data points in this investigation was departure susceptibility, the test aircraft was routinely driven to one or more of those limits. Nuisance safety trips resulted in several incomplete tasks and inconclusive departure susceptibility data. Those points were labeled as inconclusive throughout the report.

HAFA 1 and HAFA 2 Aircraft Validation

The HAFA 1 and HAFA 2 baseline aircraft were validated using flight test data obtained during validation flights. During validation flight testing, the effective time delay of HAFA 1 on the NF-16D was nearly 0.2 sec. This was deemed unacceptably high and reduced by replacing the simulated second order rate limited actuator (see Figure 5-1) with a simple adjustable software rate limit (with no dynamics). At first this may seem unreasonable, but the NF-16D actuator dynamics reasonably represent a modern actuator as described by the following Calspan provided equation:

$$\frac{\delta_{act}}{\delta_{cmd}} = \frac{20.2 \bullet 144.8 \bullet 71.4^2}{(20.2)(144.8)[0.736, 71.4]}$$

By using a simple adjustable software rate limit, the Lower Order Equivalent System (LOES) effective time delay (τ_{eff}) for the HAFA 1 configuration was reduced to 0.156 sec from step response matching and 0.124 sec from frequency response matching. The HAFA 2 LOES τ_{eff} for the step and frequency response matches were reduced to 0.156 sec and 0.105 sec, respectively. The short period natural frequency and damping ratio,

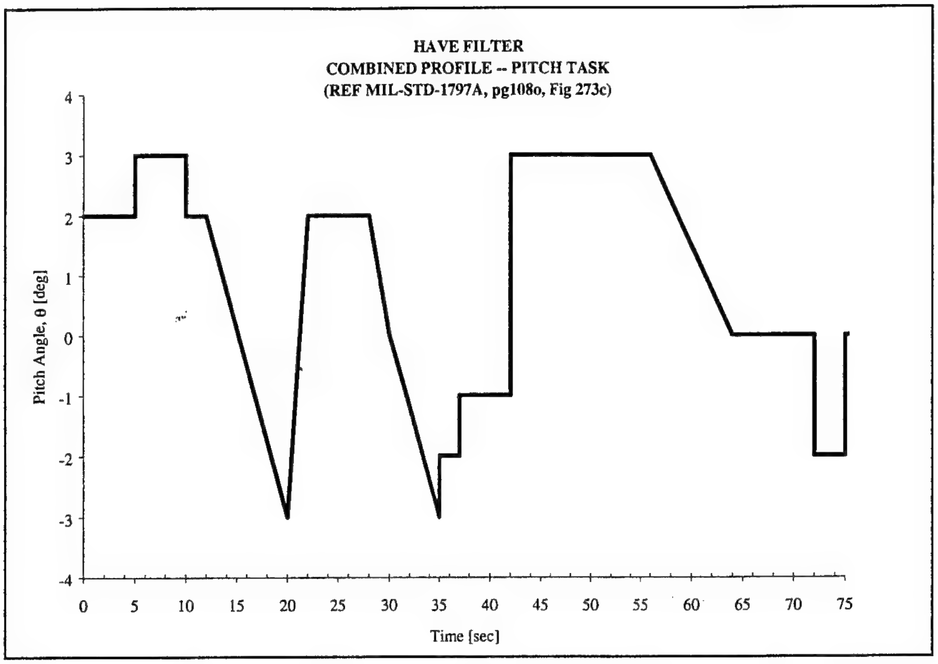


Figure 6-2. HUD Tracking Task #2, Pitch Axis

The pitch tracking task shown in Figure 6-2 was implemented in such a manner as to always command a rotation about the y-axis of the aircraft in its x-z plane, not necessarily a change in the Euler pitch angle, θ. As such, when the tracking task commanded a 3 degree pitch angle, the programmable HUD commanded a 3 degree rotation about the aircraft y-axis.

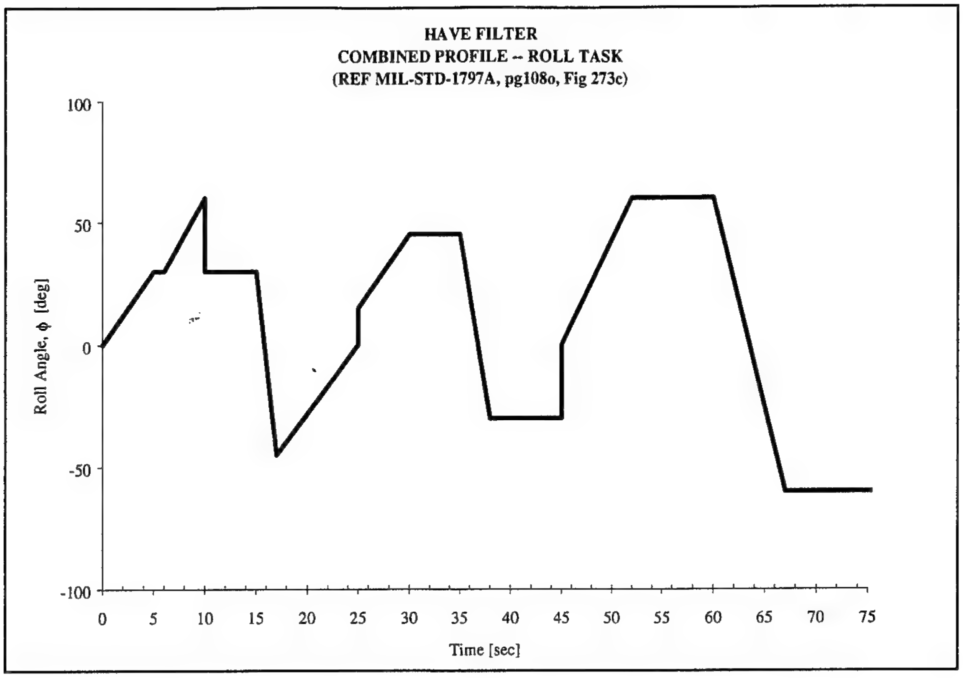


Figure 6-3. HUD Tracking Task #2, Roll Axis

As previously discussed, the VISTA was equipped with over 100 safety trips to prevent the pilot from putting the aircraft in an unrecoverable position and/or preventing structural damage. Since one of the primary data points was departure susceptibility, the test aircraft was routinely driven to one or more of those limits. After six of nine data flights, Calspan determined they could remove several nuisance derived safety trips without concern for safety and/or damage to the aircraft. The 3 safety trips removed were titled pdot_diff, qdot_diff, and rdot_diff. These safety trips were activated when differences between two angular acceleration calculations rose above a set level. These calculations determined angular accelerations (roll, pitch, and yaw accelerations) using linear accelerometers and involved extremely dirty data signals.

After these trips were removed, approximately 75 percent of the nuisance safety trips disappeared. However, pilot observations during flight, post flight evaluations of

the HUD video, safety trip information, and data traces were not always definitive in determining whether the aircraft was departing when a safety trip occurred. These points resulted in an incomplete task, unclear results, and were labeled as inconclusive.

Handling Qualities Evaluation Tasks

Phase 1, 2, and 3 handling qualities evaluations were performed. Descriptions of each phase are given below:

1. Phase 1: The evaluation pilot performed nonspecified gentle maneuvers, typically emphasizing control in the pitch axis, to get a feel for how the aircraft would handle during Phases 2 and 3.
2. Phase 2: The evaluation pilot performed high bandwidth HQDT using HUD tracking task #1. The evaluation pilot tracked the target while the safety pilot controlled the throttle to maintain 300 ±10 KCAS. After completion of the task, the pilot commented on aircraft handling qualities and assigned a pilot-induced oscillation tendency rating (PIOR) using the scale in Appendix C. Due to the nature of HQDT, Cooper-Harper handling qualities ratings were not assigned for this phase of testing.
3. Phase 3: The evaluation pilot tracked the target displayed during HUD tracking task No. 2 using operationally realistic techniques. The evaluation pilot tracked the target while the safety pilot controlled the throttle to maintain 300 ±10 KCAS. After completion of the task, the evaluation pilot assigned a PIOR and Cooper-Harper handling qualities rating (with the scale in Appendix C) using the following criteria:

Desired: Remained inside 20 milliradian diameter circle 50 percent of the time

Adequate: Remained inside 40 milliradian diameter circle 50 percent of the time

The 20 and 40 milliradian diameter circles as displayed in the HUD are shown in Figure 6-4.

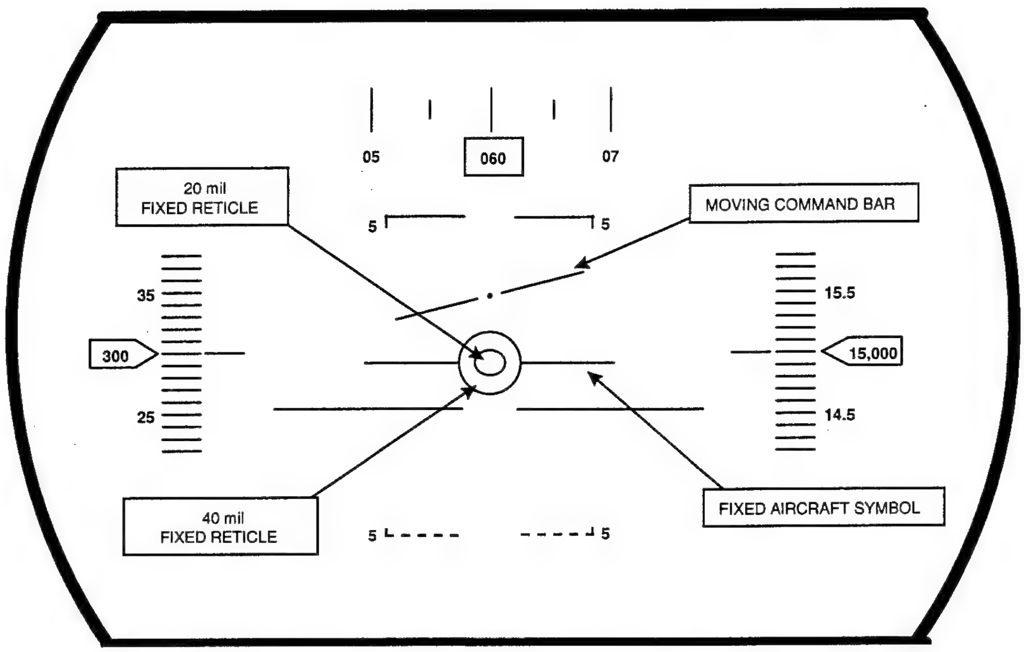


Figure 6-4. HUD Symbology

Recorded Parameters

Numerous digital and analog parameters were recorded in flight. In addition to those parameters, HUD video and the safety pilot multifunctional display (MFD) were recorded for each test point. Cockpit audio was also recorded on the HUD tape. Pilot ratings and comments were documented immediately following each flight in conjunction with the videotape review.

General Results

All test objectives were met. PIO and/or departure susceptibility was determined for both the HAFA 1 and HAFA 2 baseline aircraft and with various software rate limits with and without the RLPF. PIO tendency and Cooper-Harper ratings and pilot comments were collected at each test point.

In some cases, test points were reflown due to nuisance safety trips or inconclusive PIO and/or departure data. Appendix C contains PIO tendency and Cooper-Harper ratings with their respective pilot comments for each test point.

Available and actual test matrices are shown in Table 6-3. Actual test points are indicated by the white boxes. Gray boxes indicate test points that were available to fly but were eliminated based on data obtained during calibration flights. Some of the 22 data points were repeated resulting in 17 test points each for the HAFA 1 and HAFA 2 aircraft (34 total test points).

Table 6-3. Available and Actual Test Matrices

Configuration	SWRL (deg/s)	RLPF Thresholds (deg/s^2) None	100	250	500	750	1000	1250
HAFA 1	None	100	NA	NA	NA	NA	NA	NA
	55	110	111	112	113	114	115	116
	50	120	121	122	123	124	125	126
	45	130	131	132	133	134	135	136
	40	140	141	142	143	144	145	146
	35	150	151	152	153	154	155	156
	30	160	161	162	163	164	165	166
	25	170	171	172	173	174	175	176
	20	180	181	182	183	184	185	186
HAFA 2	None	200	NA	NA	NA	NA	NA	NA
	55	210	211	212	213	214	215	216
	50	220	221	222	223	224	225	226
	45	230	231	232	233	234	235	236
	40	240	241	242	243	244	245	246
	35	250	251	252	253	254	255	256
	30	260	261	262	263	264	265	266
	25	270	271	272	273	274	275	276
	20	280	281	282	283	284	285	286

Notes: 1. SWRL - software rate limit
2. RLPF - nonlinear rate limiter pre-filter
3. NA - not applicable
4. Gray boxes indicate available test points not flown.

Baseline Aircraft Departure/Pilot-Induced Oscillation Susceptibility

Departure tendencies for HAFA 1 and HAFA 2 during both the HQDT and operational tracking tasks are shown in Table 6-4. Similar tables are presented later for comparison between the baseline aircraft and those configurations containing the SWRL with and without the RLPF. For each departure and/or PIO susceptibility table, those configurations that did not depart are designated with an "N". Configurations that clearly departed, causing a VISTA safety trip (typically, the pitch_monitor safety trip), are labeled with a "D". Configurations where flight test data and pilot observations were inconclusive in determining whether a safety trip represented a departure or merely a

nuisance safety trip are represented by an "I". PIO tendency and Cooper-Harper ratings for "I" configurations were thrown out since the task was incomplete.

Table 6-4. Baseline Aircraft Departure Susceptibility

	Pilot A		Pilot B		Pilot C	
HAFA 1 Phase 2 Handling Qualities During Tracking	D	D*	D	N	D	D
HAFA 2 Phase 2 Handling Qualities During Tracking	I*	N	N	N	N	N
HAFA 1 Phase 3 Operational Evaluation	D	D	D	N	N	N
HAFA 2 Phase 3 Operational Evaluation	N	N	N	N	N	N

*Large amplitude HQDT task

D = Departure
N = No Departure
I = Inconclusive Data

Handling qualities during tracking (HQDT) helped to identify potential departure and PIO problems that were not observed during Phase 3 operational tracking. Departure was observed more often during HQDT than operational tracking for all HAFA 1 configurations tested and was more pilot independent. As shown in Table 6-4, the HAFA 1 aircraft departed nearly every time during HQDT and for two of the three test pilots during the operational tracking task. Pilot C was the only pilot who did not observe a departure during the operational tracking task. This demonstrates the fact that some pilots are more aggressive than others.

The HAFA 2 aircraft was not as susceptible to departure as the HAFA 1 aircraft. No departures were observed during operational tracking. One HQDT run produced inconclusive departure data.

Typical flight test data for the HAFA 1 aircraft during operational tracking are shown in Figure 6-5. Body axis pitch angle tracking is shown Figure 6-5. The HAFA 1 baseline aircraft departed controlled flight approximately 48 seconds into the tracking task (closely matching simulations from chapter 5). Departure occurred as a result of a large pull as the pilot attempted to capture the task. The pilot was unable to stop the commanded pitch rate leading to departure. This type of departure was also observed during simulations in LAMARS.

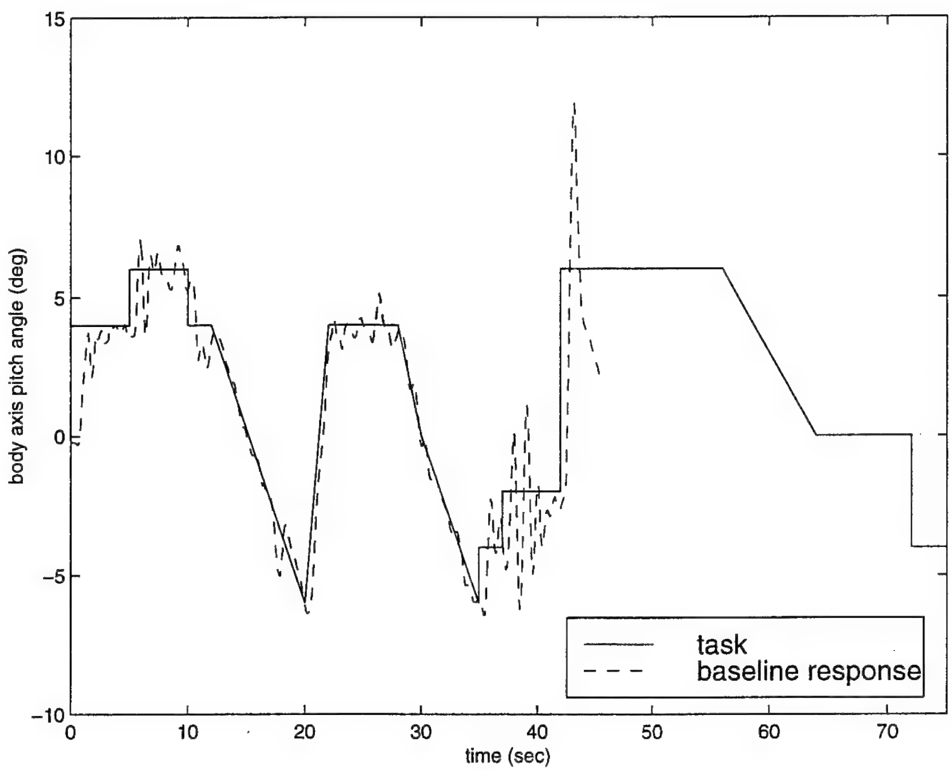


Figure 6-5. Sample HAFA 1 Baseline Tracking Response

Baseline Aircraft Handling Qualities

Handling qualities were assessed during Phase 2 HQDT and Phase 3 operational tracking tasks. The PIO and Cooper-Harper ratings for the HAFA 1 aircraft are

graphically displayed in Figure 6-6 and Figure 6-7. Likewise, ratings for the HAFA 2 aircraft are given in Figure 6-8 and Figure 6-9.

HAFA 1 Aircraft.

The HAFA 1 aircraft exhibited PIO tendencies during the HQDT task. Initial pitch response was very twitchy resulting in pitch bobbles during pitch captures. Oscillations quickly grew leading to departures in many instances.

During Phase 3 operational tracking, the aircraft departed for two pilots. A crisp initial pitch response made gross acquisition captures difficult during operational tracking. Pitch bobbles during fine tracking resulted in pilots achieving only adequate performance in many cases. Pilot C, who did not depart, thought this configuration was "on a tight rope, could depart at any time." Medium to high pilot compensation was required for all tracking tasks.

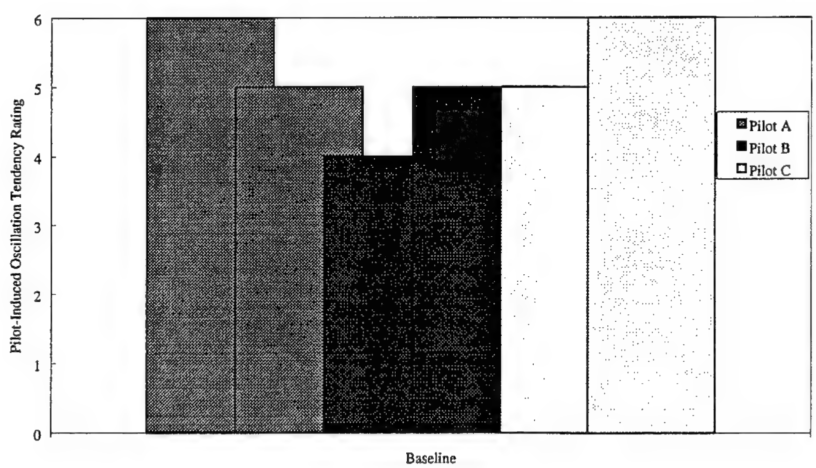


Figure 6-6. HAFA 1 Baseline HQDT PIO Tendency Ratings

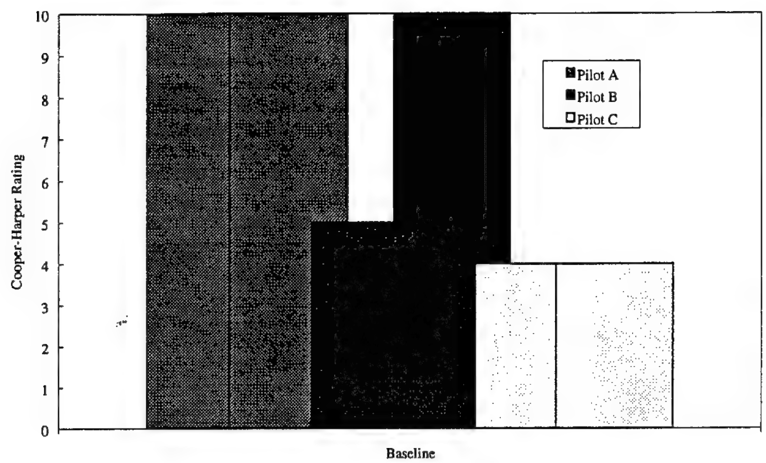


Figure 6-7. HAFA 1 Baseline Phase 3 Cooper-Harper Ratings

HAFA 2 Aircraft.

The HAFA 2 aircraft received slightly better PIO ratings than the HAFA 1 aircraft during HQDT. Pilots generally observed a small delay in pitch response followed by a steady ramp up in pitch rate. Stop to stop control inputs did not cause divergent oscillations, but caused nuisance safety trips on many occasions.

During Phase 3 operational tracking, the aircraft did not depart and received significantly better Cooper-Harper Ratings (CHR) than for the HAFA 1 aircraft. The CHR for this aircraft classified it as Level 1 despite MIL-STD 1797A (DOD, 1990) CAP predictions. Hence, CAP alone did not adequately predict aircraft handling qualities. Pilots observed an initial sluggishness and large overshoots during the larger step portions of the tracking task. Fine tracking was much easier than for the HAFA 1 aircraft as the aircraft was well behaved and predictable. One pilot surmised a larger pitch task might degrade performance because the large overshoots were difficult to arrest.

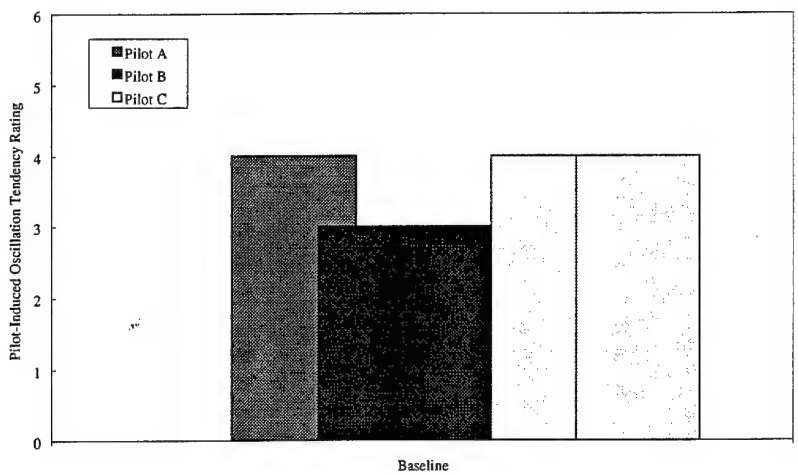


Figure 6-8. HAFA 2 Baseline HQDT PIO Tendency Ratings

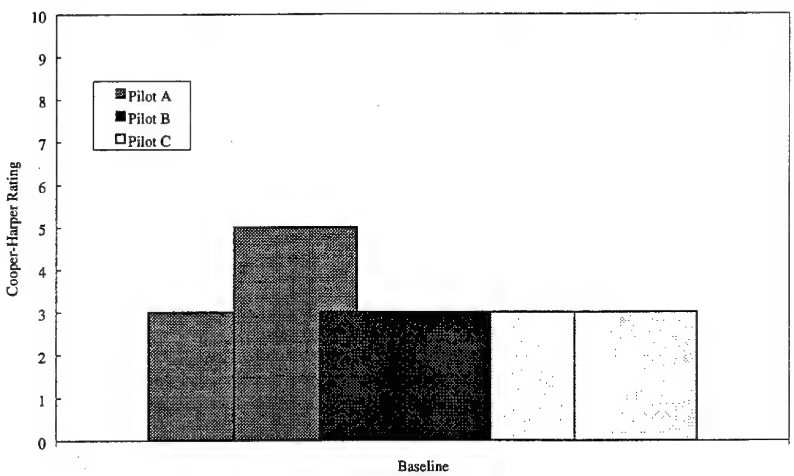


Figure 6-9. HAFA 2 Baseline Phase 3 Cooper-Harper Ratings

Software Rate Limit (SWRL) Protection Effects

Software rate limits of 50, 40, 35, 30, and 20 deg/sec were tested (see Table 6-3). A typical aircraft response with the SWRL set at 20 deg/sec is shown in Figure 6-10. Plotted in Figure 6-10 are the pilot command and the output of the SWRL (command to the outer feedback loop of the flight control system). The sawtooth pattern indicates that the pilot is commanding a higher rate of deflection of the horizontal stabilator than the SWRL setting allows. Notice that reversals do not occur in phase with the pilot

command. In addition, the slope of the SWRL Output line is 20 deg/sec, corresponding to the set SWRL for this particular configuration.

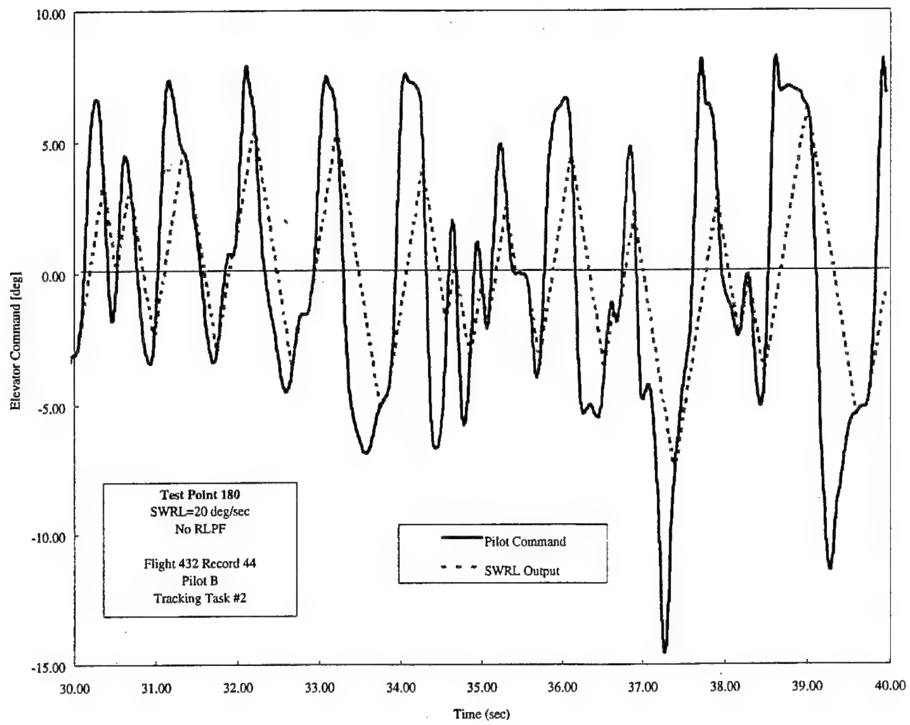


Figure 6-10. Typical SWRL Response

Departure and/or PIO Susceptibility with SWRL

Departure and/or PIO susceptibility was determined for both the HAFA 1 and HAFA 2 baseline aircraft with the addition of a SWRL on the pilot command. Departure tendencies during both the HQDT and operational tracking (HUD tracking task No. 2) tasks are identified in Table 6-5.

As the SWRL was decreased to 30 deg/sec during HQDT, departure was prevented for even the most aggressive pilot (pilot A) on the HAFA 1 aircraft as shown in Table 6-5. Again, more departures were observed for the HAFA 1 aircraft during HQDT than during operational tracking, highlighting potential problems. Data from several test

points were not sufficient to determine whether the aircraft departed or the test aircraft experienced a nuisance safety trip. Those points are identified by an "I".

Table 6-5. SWRL Effects on Departure Susceptibility

HAFA 1 Phase 2
Handling Qualities During Tracking

SWRL deg/s	Pilot A		Pilot B		Pilot C	
Baseline	D	D*	D	N	D	D
50	D		D		D	
40	D		D		D	
35	D		D		I	
30	N	N	I	I	I	N
20	I*		N	N	N	I

*Large amplitude HQDT task

HAFA 2 Phase 2
Handling Qualities During Tracking

SWRL deg/s	Pilot A		Pilot B		Pilot C	
Baseline	I*	N	N	N	N	N
50	I*		N		N	
40	N	I	I	I	N	I
35	I*		N		I	
30	N		N		N	
20	N*		N		I	

*Large amplitude HQDT task

HAFA 1 Phase 3
Operational Evaluation

SWRL deg/s	Pilot A		Pilot B		Pilot C	
Baseline	D	D	D	N	N	N
50	D		N		N	
40	D		N		N	
35	D		N		N	
30	I	N	D	D	N	N
20	N		N	N	N	N

HAFA 2 Phase 3
Operational Evaluation

SWRL deg/s	Pilot A		Pilot B		Pilot C	
Baseline	N	N	N	N	N	N
50	N		N		N	
40	I	N	N	N	N	N
35	N		N		N	
30	N		N		N	
20	N		N		N	

Notes:
1. D - departure
2. N - no departure
3. I - inconclusive data
4. Shaded boxes indicate test points that were not flown.
5. SWRL - Software Rate Limit
6. RLPF - Nonlinear Rate Limiter Pre-Filter

Minimal software rate limiting prevented departure on the HAFA 1 aircraft during Phase 3 operational tracking for all pilots except Pilot A. The aircraft departed for Pilot A with SWRL set as low as 35 deg/sec. Lower SWRL settings prevented departure for this pilot. While Pilot B did not observe departure at higher SWRL settings, the aircraft curiously departed twice with the SWRL set to 30 deg/sec. Pilot C did not observe any departures during this task.

Tracking task response for the HAFA 1 baseline aircraft is compared to the response observed for an aircraft with a software rate limit of 40 deg/sec in Figure 6-11. Compare to the baseline trace displayed in Figure 6-5. Response throughout the early

portion of the task is similar, but note the PIO that occurred around 40 sec. Eventually, both aircraft departed at nearly the same point in the task.

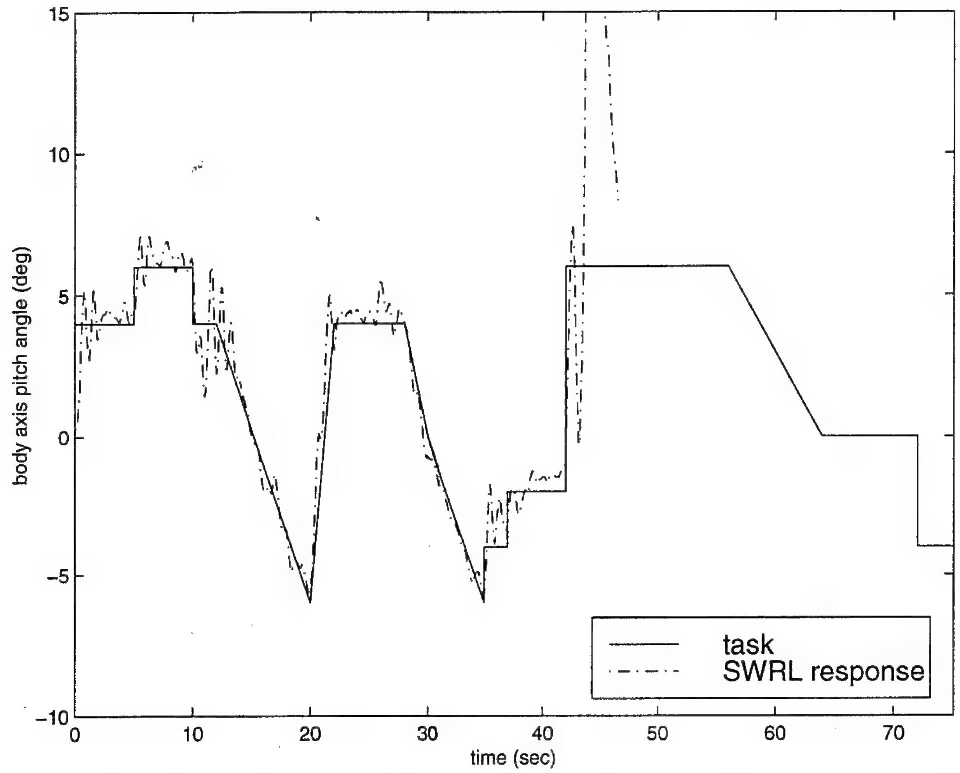


Figure 6-11. Sample HAFA 1 SWRL Tracking Response (SWRL = 40 deg/sec)

Handling Qualities with SWRL

Handling qualities were assessed during Phase 2 HQDT and Phase 3 operational tracking tasks. The PIO and Cooper-Harper ratings for the HAFA 1 aircraft are graphically displayed in Figure 6-12 and Figure 6-13. Likewise, ratings for the HAFA 2 aircraft are given in Figure 6-14 and Figure 6-15.

HAFA 1 Aircraft.

Software rate limiting the pilot command did not have an appreciable effect on PIO ratings during HQDT for the HAFA 1 aircraft through approximately 35 deg/sec.

Initial pitch response was good at all SWRL settings. The aircraft felt in-phase at higher SWRL settings, i.e. 50 deg/sec, and progressed to feeling out-of-phase at very low SWRL settings, i.e. 20 deg/sec.

In general, for the Phase 3 task, decreasing software rate limit settings resulted in higher CHR. Even though PIO ratings improved slightly below 30 deg/sec during HQDT, pilot comments indicated just the opposite during operational tracking. As the SWRL was decreased, gross acquisition became increasingly difficult as the pilots attempted to arrest fairly large overshoots. Pilots had to back out of the loop to prevent PIO with the SWRL set to 35 deg/sec or below. While fine tracking workload remained relatively constant throughout the range of SWRL settings tested, gross acquisition workload increased. Many pilots noted that a pitch rate buildup following a nice initial pitch response was unpredictable resulting in multiple, large overshoots. This behavior correlates with the tracking performance shown in Figure 6-11. At the point of departure, some pilots experienced multiple, large overshoots before the test aircraft safety trips were exceeded.

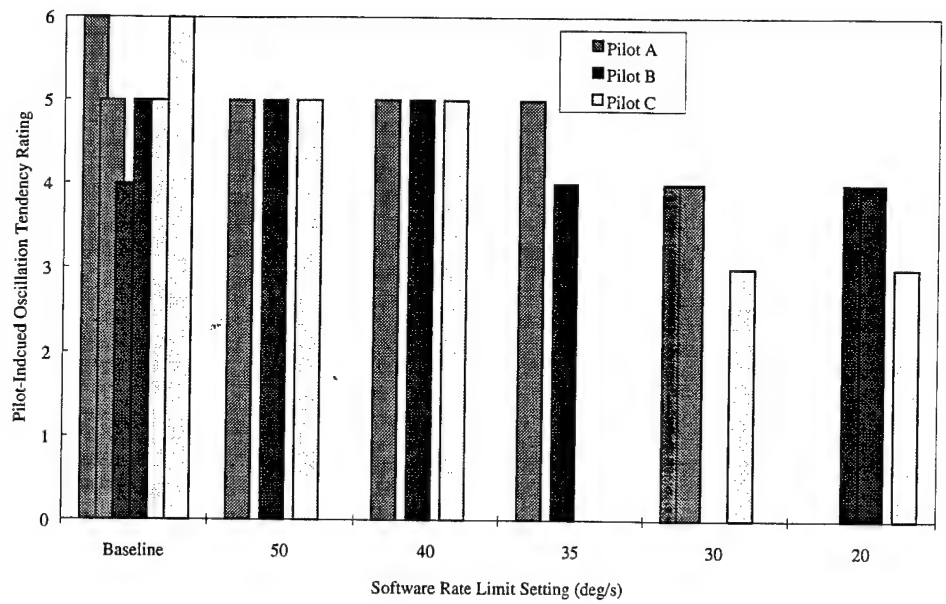


Figure 6-12. SWRL Effects on HAFA 1 HQDT PIO Tendency Ratings

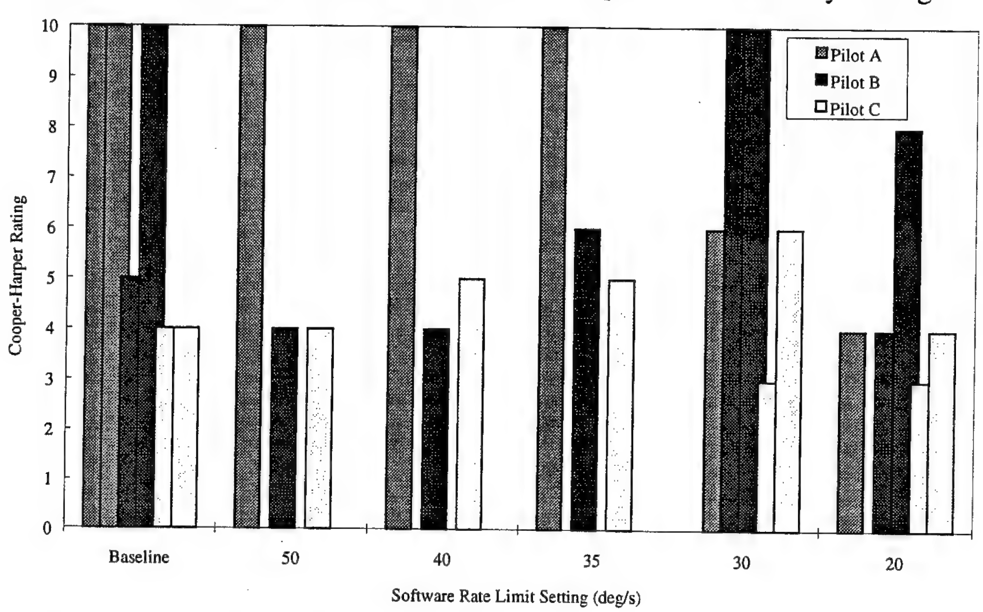


Figure 6-13. SWRL Effects on HAFA 1 Phase 3 Cooper-Harper Ratings

HAFA 2 Aircraft.

PIO ratings for the HAFA 2 aircraft were scattered across the range of SWRL settings tested. For HQDT, the pilots agreed the aircraft was generally slow to respond,

making it hard to reverse flight path. Numerous nuisance safety trips occurred during stop-to-stop HQDT because of the stick banging against the stop.

Software rate limiting had a negligible effect on CHR for the HAFA 2 aircraft during the operational tracking task. Task performance was usually adequate with more frequent desired ratings at higher SWRL settings. As mentioned previously for the baseline configuration, CHR for the HAFA 2 aircraft were significantly better than those assigned to the HAFA 1 aircraft with the same SWRL settings. The aircraft was increasingly sluggish in initial pitch response as the SWRL was decreased. This sluggishness resulted in increasing unpredictability and made gross acquisition quite difficult. Fine tracking, however, was generally enhanced by the sluggishness.

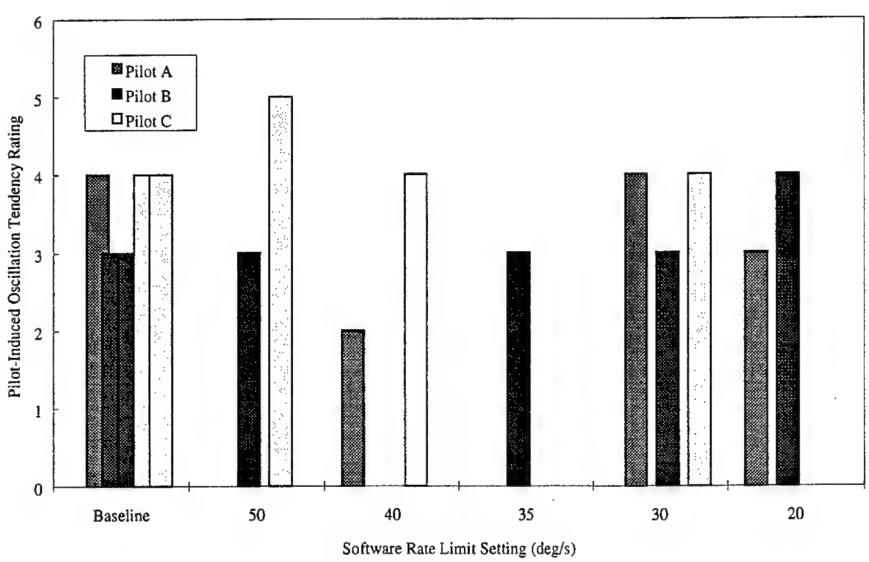


Figure 6-14. SWRL Effects on HAFA 2 HQDT PIO Tendency Ratings

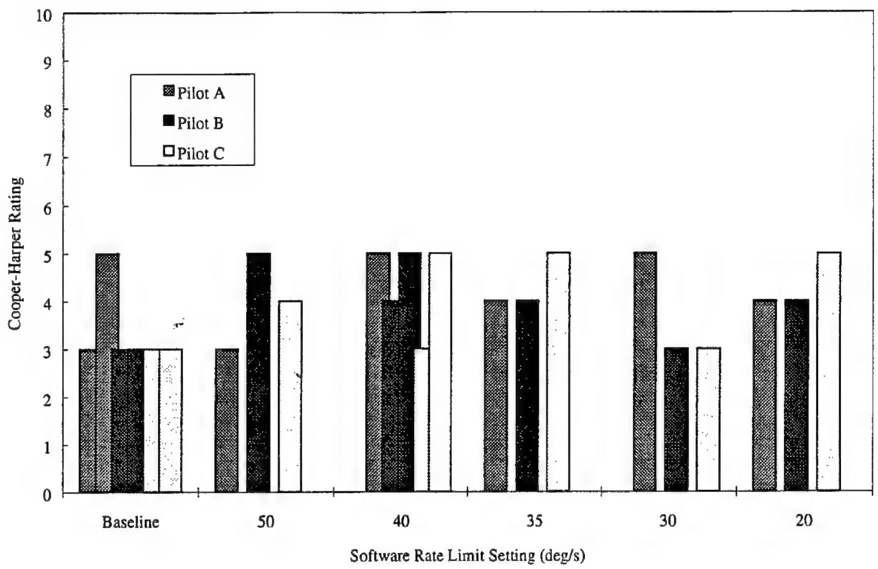


Figure 6-15. SWRL Effects on HAFA 2 Phase 3 Cooper-Harper Ratings

Rate Limiter Pre-Filter (RLPF) Plus SWRL Effects

With the SWRL only (configuration B), the SWRL output is biased off command during rate limiting (Figure 6-10) and does not stay in phase with the input. Once rate limited inputs cease the bias disappears as the output catches up to the command.

The RLPF, however, was designed to operate in conjunction with the SWRL and allow nearly in-phase reversing with the pilot command. With the RLPF plus SWRL, bias does not automatically catch up but is removed by the RLPF logic when neither the SWRL nor the stick acceleration threshold is exceeded (see Figure 2-3). For this test, the acceleration threshold for bias removal was set to 100 degrees/second squared (deg/sec^2). Initially, other threshold settings were expected to be tested (Table 6-3). As discussed in chapter 4, previous simulations using a centerstick in LAMARS showed stick accelerations above 1,000 deg/sec^2. However, calibration flights indicated the pilot was not commanding stick accelerations above 250 deg/sec^2. Actual commanded stick

accelerations typically observed for both the HAFA 1 and HAFA 2 baseline aircraft are shown in Figure 6-16.

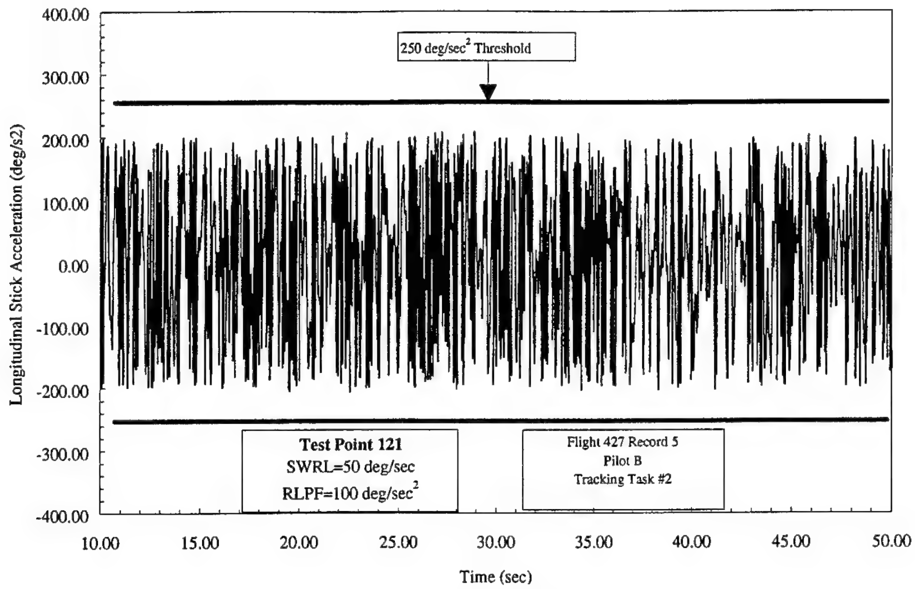


Figure 6-16. Pilot Commanded Stick Accelerations

With the acceleration threshold set above the maximum commanded acceleration value, the filter would function similarly to the SWRL alone, i.e. somewhat (but not as much) out-of-phase reversals. However, the algorithm would still command trim bias removal when the software rate limit was not exceeded. Configurations such as these, where the acceleration threshold was set too high, were not evaluated based on the simulation results of chapter 5.

For both the HAFA 1 and HAFA 2 aircraft, the RLPF functioned as designed. A typical response is shown in Figure 6-17 for a portion of the Phase 3 HUD tracking task. The data showed that the algorithm commanded in-phase reversals and trim bias removal as designed.

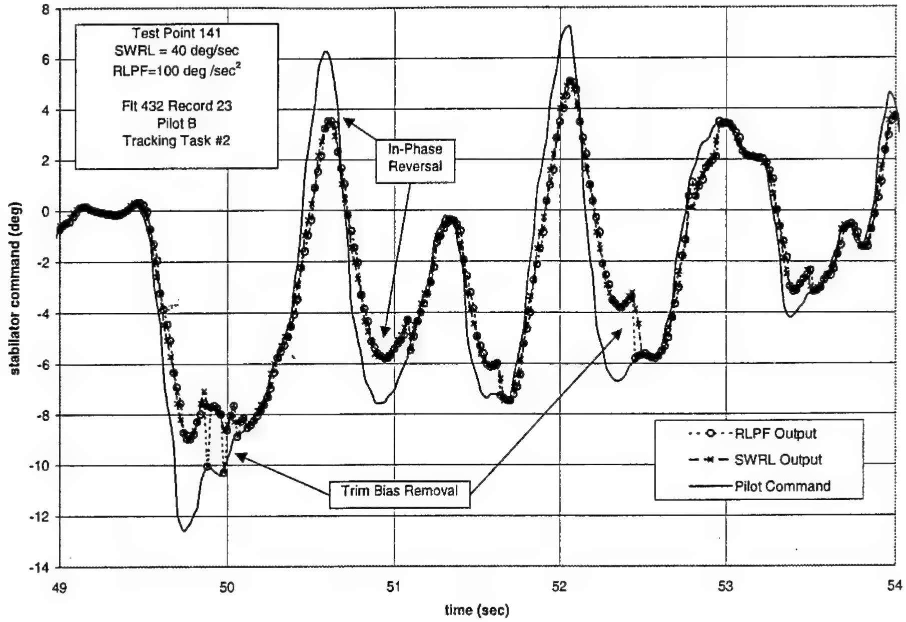


Figure 6-17. Typical RLPF Response

Departure and/or PIO Susceptibility with RLPF Plus SWRL

Departure and/or PIO susceptibility was determined for both the HAFA 1 and HAFA 2 baseline plus RLPF plus SWRL combination. Departure tendencies for these configurations for both the HQDT and operational tasks are identified in Table 6-6.

Table 6-6. RLPF Plus SWRL Effects on Departure Susceptibility

HAFA 1 Handling Qualities During Tracking

SWRL deg/s	RLPF=None Pilot A		Pilot B		Pilot C		RLPF=100 deg/s^2 Pilot A		Pilot B		Pilot C	
Baseline	D	D*	D	N	D	D						
50	D		D		D		D*		N		N	
40	D		D		D		N	D	N	D	D	N
35	D		D		I		N	N	N	I	D	N
30	N	N	I	I	I	N	N	I	N	I	N	I
20	I*		N	N	N	I	N	I*	N	I	N	I

*Large amplitude HQDT task

HAFA 1 Operational Evaluation

SWRL deg/s	RLPF=None Pilot A		Pilot B		Pilot C		RLPF=100 deg/s^2 Pilot A		Pilot B		Pilot C	
Baseline	D	D	D	N	N	N						
50	D		N		N		D		N		I	
40	D		N		N		N	N	N	N	N	N
35	D		N		N		N	I	N	N	N	N
30	I	N	D	D	N	N	N	N	N	N	N	N
20	N		N	N	N	N	N	I	N	N	N	N

HAFA 2 Handling Qualities During Tracking

SWRL deg/s	RLPF=None Pilot A		Pilot B		Pilot C		RLPF=100 deg/s^2 Pilot A		Pilot B		Pilot C	
Baseline	I*	N	N	N	N	N						
50	I*		N		N		N*		I		N	
40	N	I	I	I	N	I	N	I	I	N	I	I
35	I*		N		I		N	N	I	N	I	N
30	N		N		N		I	N	I	N	N	N
20	N*		N		I		I*	N	N	N	I	I

*Large amplitude HQDT task

HAFA 2 Operational Evaluation

SWRL deg/s	RLPF=None Pilot A		Pilot B		Pilot C		RLPF=100 deg/s^2 Pilot A		Pilot B		Pilot C	
Baseline	N	N	N	N	N	N						
50	N		N		N		N		N		N	
40	I	N	N	N	N	N	N	N	N	N	I	N
35	N		N		N		I	I	N	N	N	N
30	N		N		N		I	N	N	N	N	N
20	N		N		N		I	N	N	N	N	N

Notes: 1. D - departure
2. N - no departure
3. I - inconclusive data
4. Shaded boxes indicate test points that were not flown.
5. SWRL - Software Rate Limiter
6. RLPF - Nonlinear Rate Limiter Pre-Filter

The addition of the RLPF algorithm reduced departure susceptibility for a given SWRL setting on the HAFA 1 aircraft for both Phase 2 and 3 tasks. Following the progression of configurations from the baseline through the addition of SWRL of 40 deg/sec to the addition of the RLPF with the 35 deg/sec SWRL, one could see the difference in departure susceptibility. Where the baseline and SWRL configurations departed, the RLPF plus SWRL almost always prevented departure. Since the baseline HAFA 2 aircraft was not prone to departure, changes in departure susceptibility were not evident.

A sample tracking task response is shown in Figure 6-18. Compare to Figure 6-5 and Figure 6-11. The RLPF plus SWRL configuration has a SWRL setting equal to that Figure 6-11. As shown, the RLPF plus SWRL configuration completes the tracking task whereas the baseline and SWRL only configurations depart controlled flight around 45 seconds into the task.

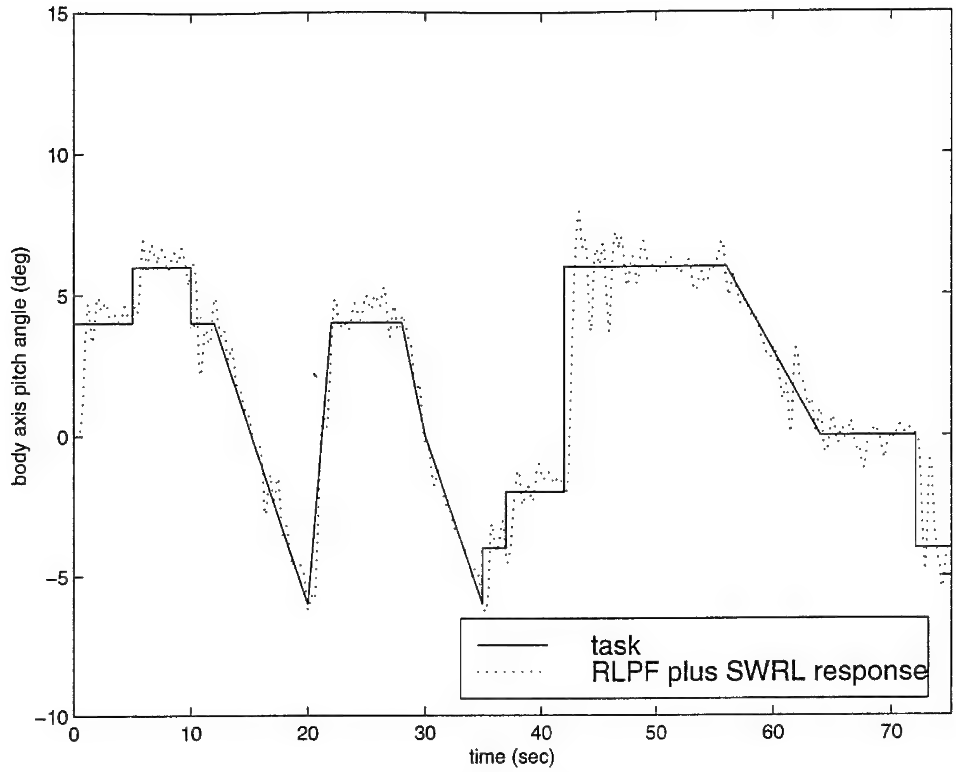


Figure 6-18. Sample HAFA 1 RLPF plus SWRL Tracking Response (SWRL = 40 deg/sec)

An evaluation of the Modified Neal-Smith pilot can be made referencing the results from Table 5-6 where the same pitch task, same RLPF threshold, and nominal noise were used. For comparison, see Table 6-6 HAFA 1 Operational Evaluation Pilot A. One difference between the two cases is the computer simulation was performed based on the NT-33 implementation of 2DU and the flight test simulation of HAFA 1 was in the NF-16D. Other differences included the use of a sidestick in flight test rather than centerstick for simulation and removal of the second noise filter in the RLPF for flight test. The computer simulation predicted a SWRL setting of 35 deg/sec or less for stability with the SWRL only configuration. The flight test result was 30 deg/sec. For the RLPF plus SWRL situation with a 100 deg/sec^2 threshold, computer simulation predicted a SWRL setting of 45 deg/sec for stability. Flight test results were at least 40

throughout the task. Poor handling qualities frequently prevented attainment of adequate criteria.

One reason for poor pilot comments and ratings for RLPF plus low SWRL settings was a large bias buildup following aggressive maneuvering that resulted in a positive command (input) but negative output or vice versa. A large bias buildup example from an operational tracking task is shown in Figure 6-19.

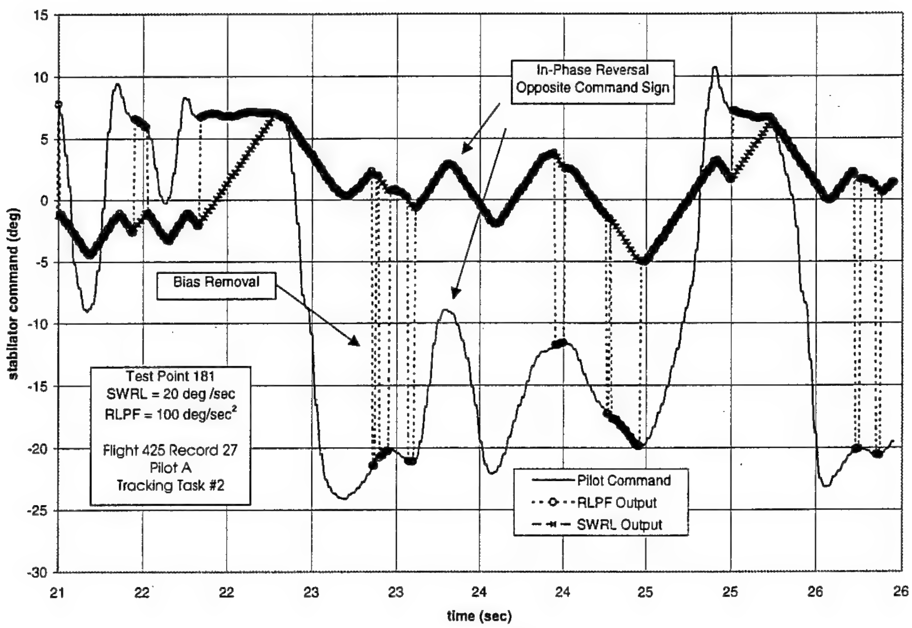


Figure 6-19. RLPF Plus Low SWRL Response (SWRL = 20 deg/sec)

This problem was observed during LAMARS testing (see chapter 4) and might me improved if the RLPF had additional logic preventing opposite sign commands from going through. One suggestion would be to zero out the command in those instances rather than letting opposite sign commands go through.

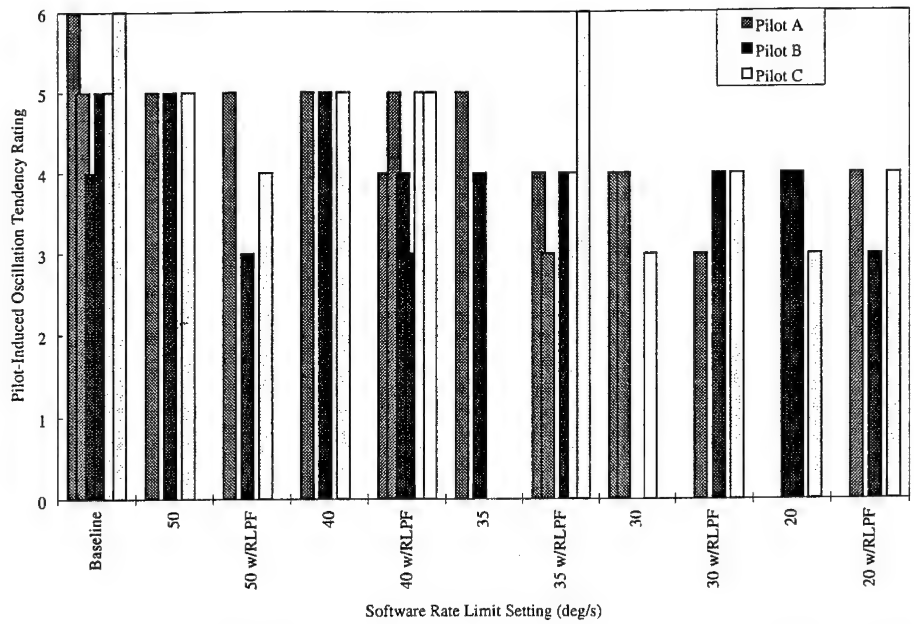


Figure 6-20. HAFA 1 RLPF Effects on HQDT PIO Tendency Ratings (RLPF = 100 deg/sec^2)

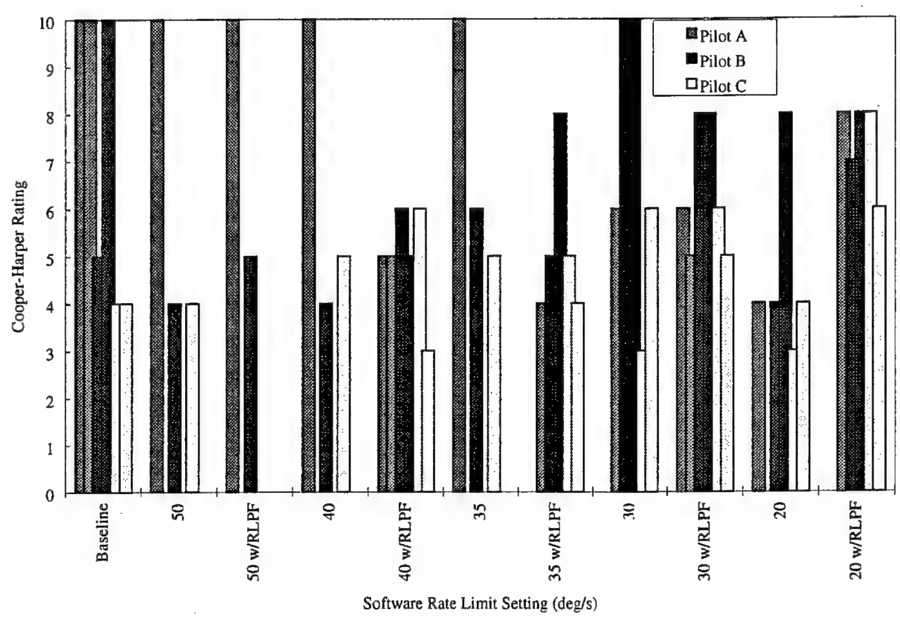


Figure 6-21. HAFA 1 RLPF Effects on Phase 3 Cooper-Harper Ratings (RLPF = 100 deg/sec^2)

HAFA 2 Aircraft.

The addition of the RLPF did not change PIO tendency ratings for the HAFA 2 aircraft during HQDT across the range of SWRL settings tested. Ratings also did not

change appreciably from the baseline configuration. Initial pitch response was quite sluggish for low software rate limit configurations. Although the initial pitch response was sluggish, large step task tracking was not degraded significantly due to the deadbeat response once pilot input was removed. There was little tendency for PIO throughout.

During operational tracking, assigned CHR for RLPF plus SWRL configurations were similar to those assigned to SWRL and baseline aircraft configurations. Pilot comments were similar to those recorded for SWRL only configurations. The aircraft was sluggish in pitch but very steady during fine tracking. There was no sense of changing flight control system gains or variable pitch rate response as was observed during the HAFA 1 evaluation with low SWRL settings. The pilots felt in command of the aircraft throughout the tracking task.

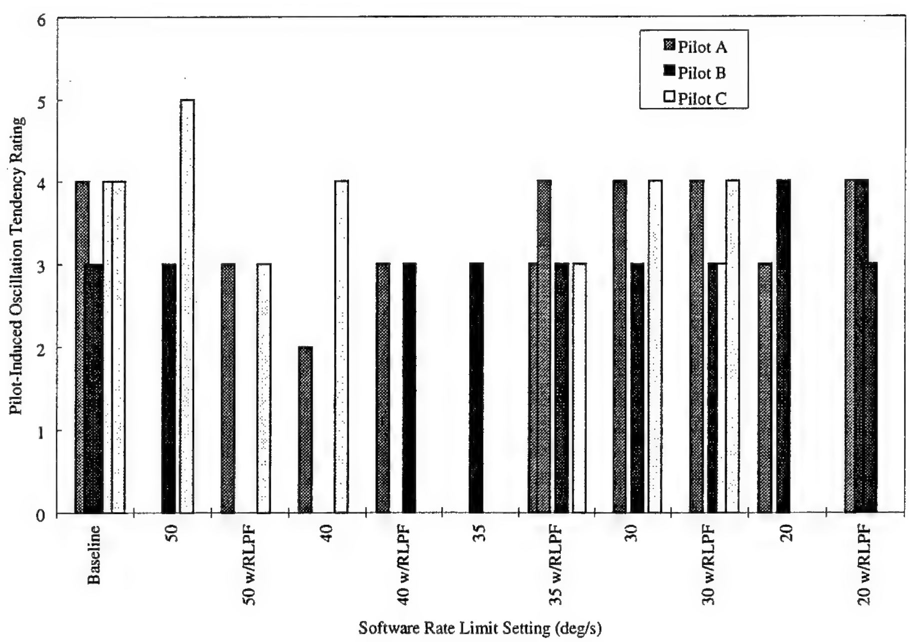


Figure 6-22. HAFA 2 RLPF Effects on HQDT PIO Tendency Ratings (RLPF = 100 deg/sec^2)

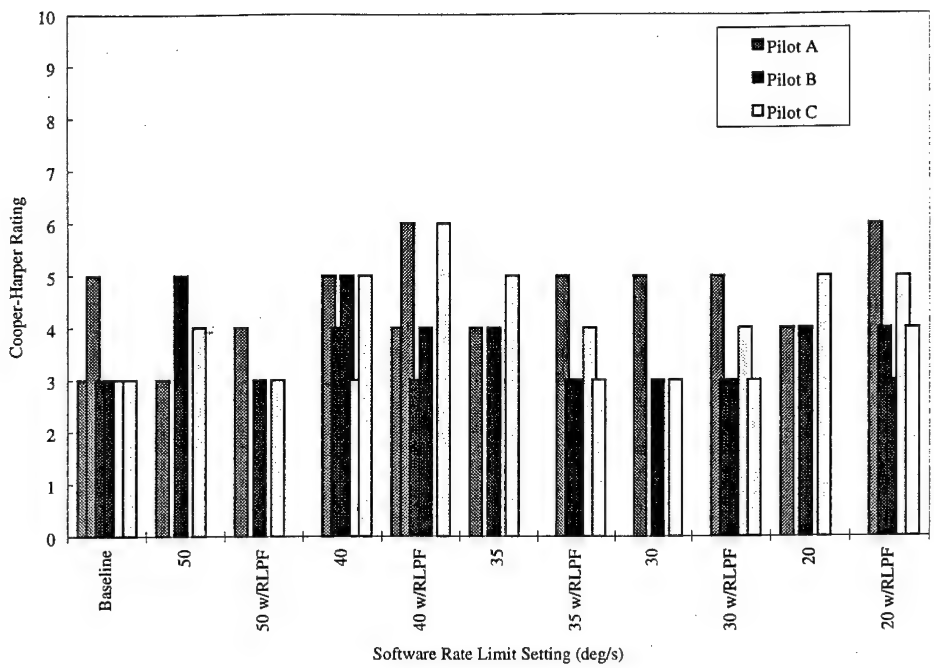


Figure 6-23. HAFA 2 RLPF Effects on Phase 3 Cooper-Harper Ratings (RLPF = 100 deg/sec^2)

VII. Conclusions and Recommendations

A nonlinear Rate Limiter Pre-Filter (RLPF) was presented in this thesis to protect from closed loop instability caused by excess phase lag induced by actuator rate limiting. It improves on previous designs in two ways: 1) effectively removes bias provided the rate limit is not set extremely low, and 2) handles noise effectively. Computer simulation, motion based piloted simulation, and flight test were accomplished.

The RLPF placed inside the feedback path of a highly augmented aircraft was successful at protecting the aircraft from departure and/or pilot-induced oscillation (PIO). Although flight test was not accomplished for this configuration, no instances of instability were observed during motion based flight simulation on LAMARS (Large Amplitude Multimode Aerospace Simulator). Even though instability was not observed, satisfactory tracking was not accomplished as the actuator rate limit was lowered.

Additionally, a different protection concept was explored during computer and flight simulation and ultimately flight tested on the VISTA NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) using a software rate limit (SWRL) with and without the RLPF on the pilot command path, rather than inside the feedback path. The SWRL and RLPF plus SWRL configurations were also successful at preventing departure and/or PIO.

The addition of the SWRL showed promise at protecting the aircraft from instability, but depending on the level of instability the SWRL setting may be so low that inadequate handling qualities may occur. This may be observed as a sluggish initial pitch

response and in some cases, the phase lag added by the SWRL may induce departure and/or PIO.

The RLPF plus SWRL combination resulted in the strongest departure and/or PIO protection scheme and could allow a higher SWRL setting (than using the SWRL alone) enabling better handling qualities. However, if a low SWRL setting is used, the RLPF plus SWRL combination can result in significantly degraded handling qualities. Although bias removal was inherent in the RLPF algorithm, a large bias buildup during aggressive maneuvering sometimes led to apparent nonresponsive or opposite pitch commands.

The MIL-STD 1797A Control Anticipation Parameter (CAP) was unreliable for predicting handling qualities ratings for the flight test. The predicted level 1 configuration (HAFA 1) was evaluated more like a level 2 aircraft and the predicted level 3 configuration (HAFA 2) was evaluated more like a level 1 aircraft.

The handling qualities during tracking (HQDT) technique as defined by the USAF Test Pilot School (TPS) was valuable at uncovering PIO and/or departure susceptibility. The strength of the technique is more pilot independent results. This technique cannot guarantee stability, but can serve as a confidence builder for design.

The use the Modified Neal-Smith pilot model for this study enabled predictions for the LAMARS and NF-16D flight test evaluations. Comparisons between computer and LAMARS simulations were good for some situations and poor for others. Comparisons between computer simulations and flight test were pilot dependent pointing out the variation in human pilot characteristics.

Recommendations for further research include adding extra logic to the RLPF to prevent opposite sign input/output relationships. Further flight test could investigate center and sidestick comparisons using the RLPF. Nuisance NF-16D VISTA safety trips prevented useful data at several data points. Unnecessary safety trips should be removed during calibration test flights. Flight test data from the HAVE FILTER project should be incorporated back into computer simulation using a validated aircraft model. With a validated aircraft model, various pilot models could be used for comparison with flight test data to determine the most effective pilot model for this type of study.

Appendix A: Matlab Files

lin_abcd.m MATLAB™ file from CALSPAN for NT-33 stability derivatives and state-space formulation

```
%Latest and Greatest  4/18/97 from A. Crassidis
%lin_abcd.m
%NT_T33: H=9300ft, V=473ft/sec, IAS=248knots
%Computes linear ABCD matrices
%Lateral/Directional and Longitudinal

format short e

r2d=180/pi;
d2r=pi/180;
g=32.172; %(ft/sec)

%NT_T33 geometric data
S=234.0; %(ft**2)
B=37.54; %(ft)
Cbar=6.72; %(ft)
W=442.026*g; %(lbs)
mass=W/g; %(slugs)
Ixx=23624.5; %(slugs-ft**2)
Iyy=21000.0; %(slugs-ft**2)
Izz=43898.0; %(slugs-ft**2)
Ixz=480.0;   %(slugs-ft**2)

FR=input('Input fuel remaining (gallons) [575]: ');
if(isempty(FR)')
 FR=575.0;
end
%FR=484;

Vtrim=input('Input trim velocity (ft/sec) [490]: ');
if(isempty(Vtrim)')
 Vtrim=490;
end

height=input('Input aircraft height (ft) [10000]: ');
if(isempty(height)')
 height=10000;
end

height_table=[
0.0;
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
7000.0
8000.0
9000.0
10000.0
11000.0
12000.0
13000.0
14000.0
15000.0
16000.0
17000.0
18000.0
19000.0
20000.0
21000.0
22000.0
23000.0
24000.0
25000.0
26000.0
27000.0
28000.0
29000.0
30000.0
31000.0
32000.0
33000.0
34000.0
35000.0
36000.0
37000.0
];
```

```
rho_table=[
1.0000
0.9711
0.9428
0.9151
0.8881
0.8617
0.8359
0.8106
0.7860
0.7620
0.7385
0.7156
0.6932
0.6713
0.6500
0.6292
0.6090
0.5892
0.5699
0.5511
0.5328
0.5150
0.4976
0.4806
0.4642
0.4481
0.4325
0.4173
0.4025
0.3881
0.3741
0.3605
0.3473
0.3345
0.3220
0.3099
0.2971
0.2844
];

rho_table=rho_table*0.002378;

tab=[height_table rho_table];
rho=table1(tab,height);

mass=(11074.0+6.5*FR)/32.17;
Iyy = 21000.0;
Ixz = 480.0;

if(FR<=350.0)
 Ixx=12500.0+4.0*(FR-100.0);
 Izz=12597.0+53.06*FR;
else
 Ixx=13500.0+75.556*(FR-350.0);
 Izz=31168.0+95.0*(FR-350.0);
end

%NT_T33 trim values
de_d=1.2000;  %elevator
alpha_d=2.1491;

de_r=de_d*d2r;
alpha_r=alpha_d*d2r;
csc=cos(alpha_r);
ssc=sin(alpha_r);
q_d=0.0;
q_r=q_d*d2r;
%Vtrim=470.00; %(ft/sec) %long ID
%Vtrim=490.00; %(ft/sec) %lat ID rec3
%Vtrim=506.00; %(ft/sec) %lat ID rec2
%rho=1.7920e-03; %long D
%rho=1.7562e-03; %lat ID
Qbar=0.5*rho*Vtrim*Vtrim; %(lbs/ft**2)
Utrim=Vtrim*csc; %(ft/sec)

%NT-T33 non-dimensional aero derivatives (in "stability" axis), 1/rad
Cla_s    = 9.57895E-02/(0.95*d2r);
Clad_s   = 0.00000E+00/d2r;  %-2e-2/d2r
Clq_s    = 0.00000E+00/d2r;  %5e-01/d2r;
Clde_s   = 4.00000E-03/d2r;
Clu_s    = 0.00000E+00;
Clo_s    = mass*g/(Qbar*S)-(Cla_s*alpha_r+Clq_s*q_r+Clde_s*de_r);
CL_s=Clo_s+Cla_s*alpha_r+Clq_s*q_r+Clde_s*de_r;

Cma_s    = -5.25778E-03/d2r;
Cmad_s   = -8.40000E-02/d2r;
Cmq_s    = -1.99048E-01/d2r;
Cmde_s   = -1.22857E-02/d2r;
Cmu_s    = 0.00000E+00;
Cmo_s    = -(Cma_s*alpha_r+Cmq_s*q_r+Cmde_s*de_r);
CM_s=Cmo_s+Cma_s*alpha_r+Cmq_s*q_r+Cmde_s*de_r;
```

```
Cdo_s   = 6.45000E-02;
Cda_s   = 7.68431E-03/d2r;
Cdad_s  = 0.00000E+00/d2r;
Cdq_s   = 0.00000E-00/d2r;
Cdde_s  = 5.00000E-03/d2r;
Cdu_s   = 0.00000E+00;
CD_s=Cdo_s+Cda_s*alpha_r+Cdq_s*q_r+Cdde_s*de_r;

Cyo_b   = 0.0;
Cyb_b   = -9.17309E-03/d2r;
Cyp_b   = -1.87501E-05/d2r;
Cyr_b   = 2.99694E-03/d2r;
Cyda_b  = 1.10223E-05/d2r;
Cydr_b  = 1.34821E-03/d2r;
CY_b=0.0;

C1o_b   = 0.0;
C1b_b   = -1.33127E-03/d2r;
C1p_b   = -1.02767E-02/d2r;
C1r_b   = 2.21387E-03/d2r;
C1da_b  = -1.69972E-03/d2r;
C1dr_b  = 3.96060E-05/d2r;
C1_b=0.0;

Cno_b   = 0.0;
Cnb_b   = 1.04895E-03/d2r;
Cnp_b   = -3.03637E-04/d2r;
Cnr_b   = -3.73719E-03/d2r;
Cnda_b  = 7.03864E-05/d2r;
Cndr_b  = -6.01806E-04/d2r;
CN_b=0.0;

%Convert to NT-T33 "body" axis system
Cmo_b   = Cmo_s;
Cma_b   = Cma_s;
Cmad_b  = Cmad_s;
Cmq_b   = Cmq_s;
Cmde_b  = Cmde_s;
Cmu_b   = Cmu_s;
CM_b    = CM_s;

Clo_b   = Clo_s*csc + Cdo_s*ssc;
Cla_b   = Cla_s*csc + Cda_s*ssc;
Clad_b  = Clad_s*csc;
Clq_b   = Clq_s*csc + Cdq_s*ssc;
Clde_b  = Clde_s*csc + Cdde_s*ssc;
Clu_b   = Clu_s*csc + Cdu_s*ssc;
CL_b    = CL_s*csc + CD_s*ssc;

Cdo_b   = Cdo_s*csc - Clo_s*ssc;
Cda_b   = Cda_s*csc - Cla_s*ssc;
Cdad_b  = Cdad_s*csc;
Cdq_b   = Cdq_s*csc - Clq_s*ssc;
Cdde_b  = Cdde_s*csc - Clde_s*ssc;
Cdu_b   = Cdu_s*csc - Clu_s*ssc;
CD_b    = CD_s*csc - CL_s*ssc;

%Compute NT-T33 longitudinal dimensional derivatives (body axis)
Xu_b=-(Qbar*S*(Cdu_b+2.0*CD_b))/(mass*Vtrim); %(1/sec)
Xw_b=-(Qbar*S*(Cda_b-CL_b))/(mass*Vtrim); %(1/sec)
Xa_b=Xw_b*Vtrim; %(ft/sec**2)
Xwd_b=(Qbar*S*Cbar*Clad_s*ssc)/(2.0*Vtrim*Vtrim*mass); %(---)
Xad_b=Xwd_b*Vtrim; %(ft/sec)
Xq_b=-(Qbar*S*Cbar*Cdq_b)/(2.0*Vtrim*mass); %(ft/sec)
Xde_b=-(Qbar*S*Cdde_b)/mass; %(ft/sec**2)
```

```
Zu_b=-(Qbar*S*(Clu_b+2.0*CL_b))/(mass*Vtrim); %(1/sec)
Zw_b=-(Qbar*S*(Cla_b+CD_b))/(mass*Vtrim); %(1/sec)
Za_b=Zw_b*Vtrim; %(ft/sec**2)
Zwd_b=-(Qbar*S*Cbar*Clad_b)/(2.0*Vtrim*Vtrim*mass); %(---)
Zad_b=Zwd_b*Vtrim; %(ft/sec)
Zq_b=-(Qbar*S*Cbar*Clq_b)/(2.0*Vtrim*mass); %(ft/sec)
Zde_b=-(Qbar*S*Clde_b)/mass; %(ft/sec**2)

Mu_b=(Qbar*S*Cbar*(Cmu_b+2*CM_b))/(Iyy*Vtrim); %(1/ft-sec)
Ma_b=(Qbar*S*Cbar*Cma_b)/Iyy; %(1/sec**2)
Mad_b=(Qbar*S*Cbar*Cbar*Cmad_b)/(2*Iyy*Vtrim); %(1/sec)
Mq_b=(Qbar*S*Cbar*Cbar*Cmq_b)/(2*Iyy*Vtrim); %(1/sec)
Mde_b=(Qbar*S*Cbar*Cmde_b)/Iyy; %(1/sec**2)

%Form longitudinal A and B matrices (body axis)
%states[U/Uo alpha(rad) Q(rad/s) theta(rad)]
%control[de(rad) dz(rad) dr(rad)]
A_lon_b=[Xu_b Xa_b/Vtrim Xq_b/Vtrim-ssc -csc*g/Vtrim
    Zu_b Za_b/Vtrim (1.0+Zq_b/Vtrim) -ssc*g/Vtrim
    Mu_b*Vtrim Ma_b Mq_b 0
    0 0 1 0];
B_lon_b=[Xde_b/Vtrim
    Zde_b/Vtrim
    Mde_b
    0      ];
A_lon_body=A_lon_b;
B_lon_body=B_lon_b;

%Add contributions of alpha dot aero derivatives (body axis)
A_lon_body(2,:)=A_lon_b(2,:)/(1-Zad_b/Vtrim);
B_lon_body(2,:)=B_lon_b(2,:)/(1-Zad_b/Vtrim);
A_lon_body(1,:)=Xad_b*A_lon_body(2,:)+A_lon_b(1,:);
B_lon_body(1,:)=Xad_b*B_lon_body(2,:)+B_lon_b(1,:);
A_lon_body(3,:)=Mad_b*A_lon_body(2,:)+A_lon_b(3,:);
B_lon_body(3,:)=Mad_b*B_lon_body(2,:)+B_lon_b(3,:);

%Convert longitudinal A and B matrices (body axis)
%states[U(ft/s) alpha(deg) Q(deg/s) theta(deg)]
%control[de(deg) df(deg) dth(deg) dlef(deg)]
T2rad=[Vtrim 0 0 0;0 r2d 0 0;0 0 r2d 0;0 0 0 r2d];
A_lon_body=T2rad*A_lon_body*inv(T2rad);
B_lon_body(1,:)=B_lon_body(1,:)*Vtrim*d2r;

%Compute NT-T33 lateral dimensional derivatives (body axis)
Yb_b=(Qbar*S*Cyb_b)/mass; %(ft/sec**2)
Yp_b=(Qbar*S*B*Cyp_b)/(2*mass*Vtrim); %(ft/sec)
Yr_b=(Qbar*S*B*Cyr_b)/(2*mass*Vtrim); %(ft/sec)
Yda_b=(Qbar*S*Cyda_b)/mass; %(ft/sec**2)
Ydr_b=(Qbar*S*Cydr_b)/mass; %(ft/sec**2)

Lb_b=(Qbar*S*B*C1b_b)/Ixx; %(1/sec**2)
Lp_b=(Qbar*S*B*B*C1p_b)/(2*Ixx*Vtrim); %(1/sec)
Lr_b=(Qbar*S*B*B*C1r_b)/(2*Ixx*Vtrim); %(1/sec)
Lda_b=(Qbar*S*B*C1da_b)/Ixx; %(1/sec**2)
Ldr_b=(Qbar*S*B*C1dr_b)/Ixx; %(1/sec**2)

Nb_b=(Qbar*S*B*Cnb_b)/Izz; %(1/sec**2)
Np_b=(Qbar*S*B*B*Cnp_b)/(2*Izz*Vtrim); %(1/sec)
Nr_b=(Qbar*S*B*B*Cnr_b)/(2*Izz*Vtrim); %(1/sec)
Nda_b=(Qbar*S*B*Cnda_b)/Izz; %(1/sec**2)
Ndr_b=(Qbar*S*B*Cndr_b)/Izz; %(1/sec**2)

%Form lateral A and B matrices (body axis)
%states[beta(rad) P(rad/s) R(rad/s) phi(rad)]
%control[da(rad) dr(rad)]
```

```
A_lat_b=[Yb_b/Vtrim  Yp_b/Vtrim+ssc  Yr_b/Vtrim-csc  (g*csc)/Vtrim
      Lb_b      Lp_b       Lr_b       0
      Nb_b      Np_b       Nr_b       0
      0         1          tan(alpha_r)  0      ];

B_lat_b=[Yda_b/Vtrim  Ydr_b/Vtrim
      Lda_b     Ldr_b
      Nda_b     Ndr_b
      0         0       ];

%Convert lateral A and B matrices (body axis)
%states[beta(deg) P(deg/s) R(deg/s) phi(deg)]
%control[da(deg) dr(deg)]
T2rad=[r2d 0 0 0;0 r2d 0 0;0 0 r2d 0;0 0 0 r2d];
A_lat_body=T2rad*A_lat_b*inv(T2rad);
B_lat_body=B_lat_b;

% eric's stuff
a=A_lon_body;
b=B_lon_body;
c=eye(4);
d=zeros(4,1);
% alpha dot output
c(5,:)=a(2,:);
d(5,:)=b(2,:);

alat=A_lat_body;
blat=B_lat_body;
clat=eye(4);
dlat=zeros(4,2);
% beta dot output
clat(5,:)=alat(1,:);
dlat(5,:)=blat(1,:);
```

nspilot.m MATLAB™ file

```
%
%         Thesis Modified Neal-Smith Pilot Model
%         for TPS Spring 97 A/C 2DU
%         by Capt Mike Chapa
%
w=logspace(-2,3);
s=i*w;
pd=0.25;
YCnum=-7431387.9*(s+.0378).*(s+1.259);
YCden=s.^7+128.27*s.^6+8136.97*s.^5+125574.1*s.^4+754053.5*s.^3+2523965.2*s.^2+8903.4*s+15545.2;
TFYC=YCnum./YCden;
GYC=20*log10(abs(TFYC));
PHIYCx=atan2(imag(TFYC),real(TFYC));
PHIYC=unwrap(PHIYCx)*180/pi;
java=1;
while java==1
kp=input('enter kp : ');
Tp1=input('enter Tp1 : ');
Tp2=input('enter Tp2 : ');
YPnum=kp*100*exp(-pd*s).*(Tp1*s+1).*(5*s+1);
YPden=(Tp2*s+1).*s.*(s+100);
TFYP=YPnum./YPden;
GYP=20*log10(abs(TFYP));
PHIYPx=atan2(imag(TFYP),real(TFYP));
PHIYP=unwrap(PHIYPx)*180/pi;
NG=GYC+GYP;
NP=PHIYC+PHIYP;
figure(1);
ngrid2('new');
hold on;
plot(NP,NG,'w');
grid on;
title('Nichols Chart for YpYc under Mod-Neal/Smith Criteria');
figure(2);
ngrid2('new');
hold on;
plot(NP,NG);
axis([-180 -90 -5 0]);
grid on;
title('Nichols Chart for YpYc under Mod-Neal/Smith Criteria');
figure(3);
subplot(2,1,1),semilogx(w,NG);
grid on;
hold on;
subplot(2,1,2),semilogx(w,NP);
grid on;
title('Bode plot for YpYc');
subplot(2,1,2),axis([1 5 -180 -90]);
figure(4);
subplot(2,1,1),semilogx(w,NG);
grid on;
hold on;
subplot(2,1,2),semilogx(w,NP);
grid on;
title('Bode plot for YpYc');
subplot(2,1,2),axis([1 5 -160 -130]);
java=input('enter 0 to quit : ');
end
```

Appendix B: Baseline Aircraft (HAFA 1 and HAFA 2) Configurations Flight Test Verification

The following transfer functions describe the lower order equivalent system (LOES) matching model and control anticipation parameter (CAP) values derived from the NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA) flight step responses (Figure B-1 and Figure B-2) for HAFA 1 and HAFA 2 aircraft, where:

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(K)(T_{\theta 2}s+1)e^{-\tau_d s}}{\left(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}{}^2\right)}$$

$$CAP = \left(\omega_{sp}{}^2\right) / \left(\left(V_{T_o} / g\right) / T_{\theta 2}\right)$$

LEVEL 1 (300 knots at 15,000 feet, V_{to} = 626.72 feet/sec) Figure B-1

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(18.998)(0.65s+1)e^{-0.156s}}{\left(s^2+2(0.7)(4.64)s+4.64^2\right)}$$

CAP=0.718 sec^{-2}

LEVEL 3 (300 knots at 15,000 feet, V_{to} = 626.72 feet/sec) Figure B-2

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(21.816)(0.65s+1)e^{-0.156s}}{\left(s^2+2(0.654)(1.8)s+1.8^2\right)}$$

CAP=0.108 sec^{-2}

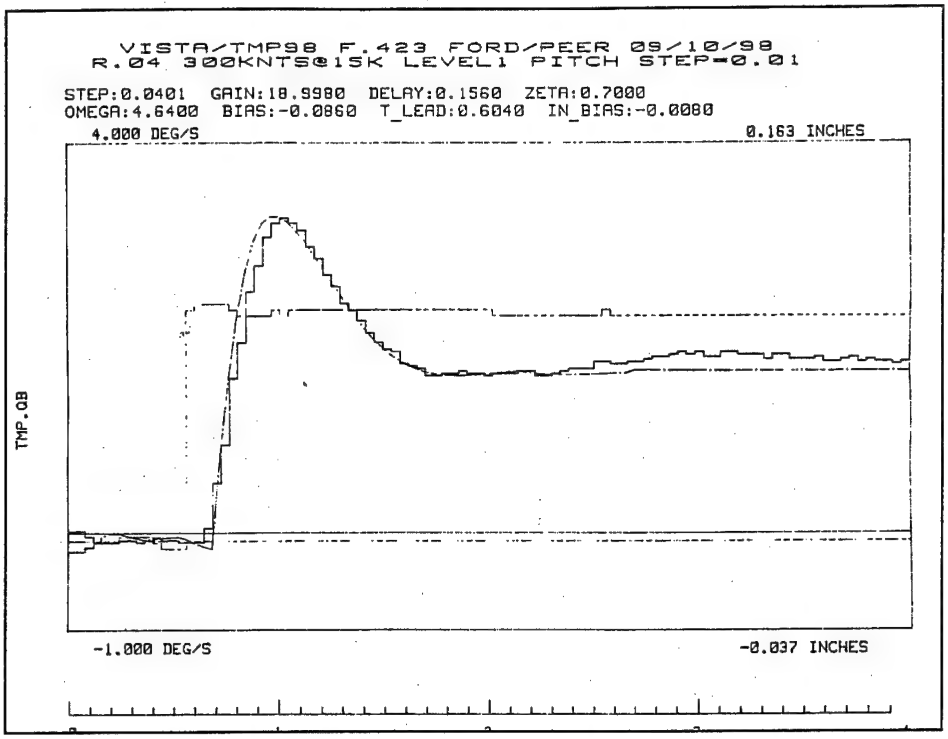


Figure B-1. Time History Matching of Lower Order Equivalent System and Flight Data (Level 1 Aircraft)

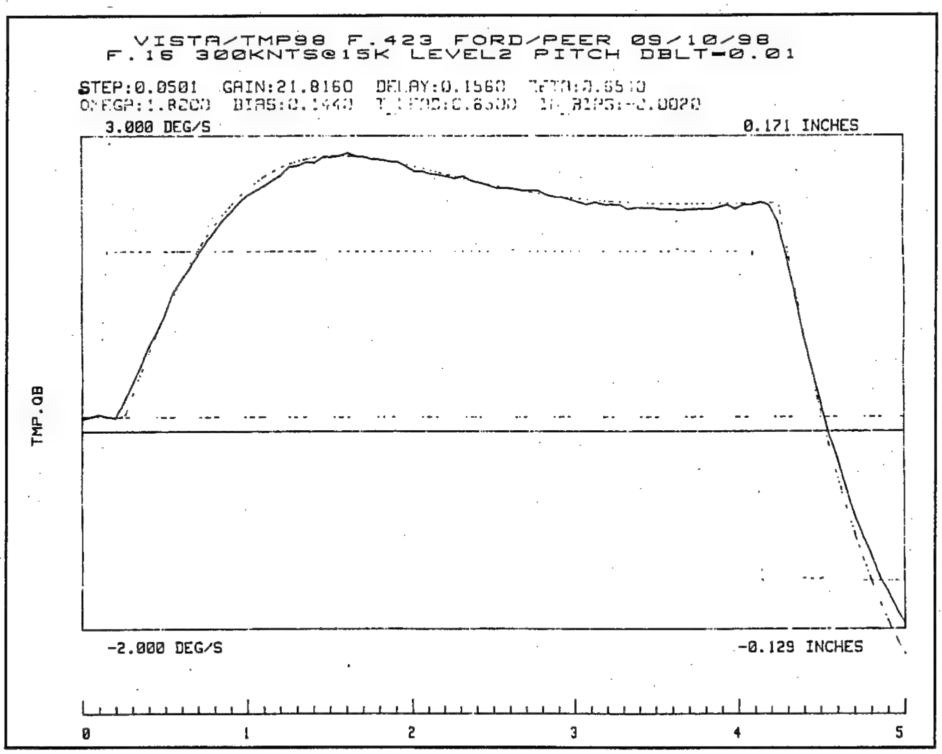


Figure B-2. Time History Matching of Lower Order Equivalent System and Flight Data (Level 3 Aircraft)

The following transfer functions describe the LOES matching model and CAP values derived from VISTA frequency responses (reference Figure B-3 and Figure B-4).

LEVEL 1 (300 knots at 15,000 feet, V_{to} = 626.72 feet/sec) Figure B-3

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(17.0)(0.65s+1)e^{-0.124s}}{\left(s^2+2(0.7)(5.2)s+5.2^2\right)}$$

CAP=0.902 sec^{-2}

LEVEL 3 (300 knots at 15,000 feet, V_{to} = 626.72 feet/sec) Figure B-4

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(21.0)(0.63s+1)e^{-0.105s}}{\left(s^2+2(0.75)(2.0)s+2.0^2\right)}$$

CAP=0.130 sec^{-2}

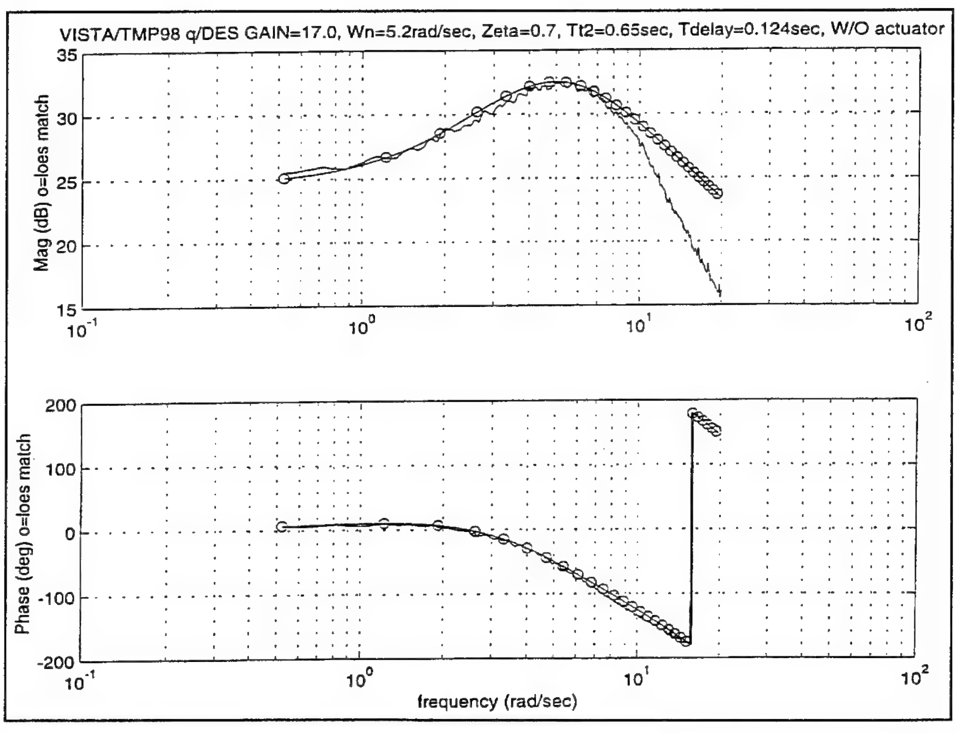


Figure B-3. Frequency Matching of Lower Order Equivalent System and Flight Data (Level 1 Aircraft)

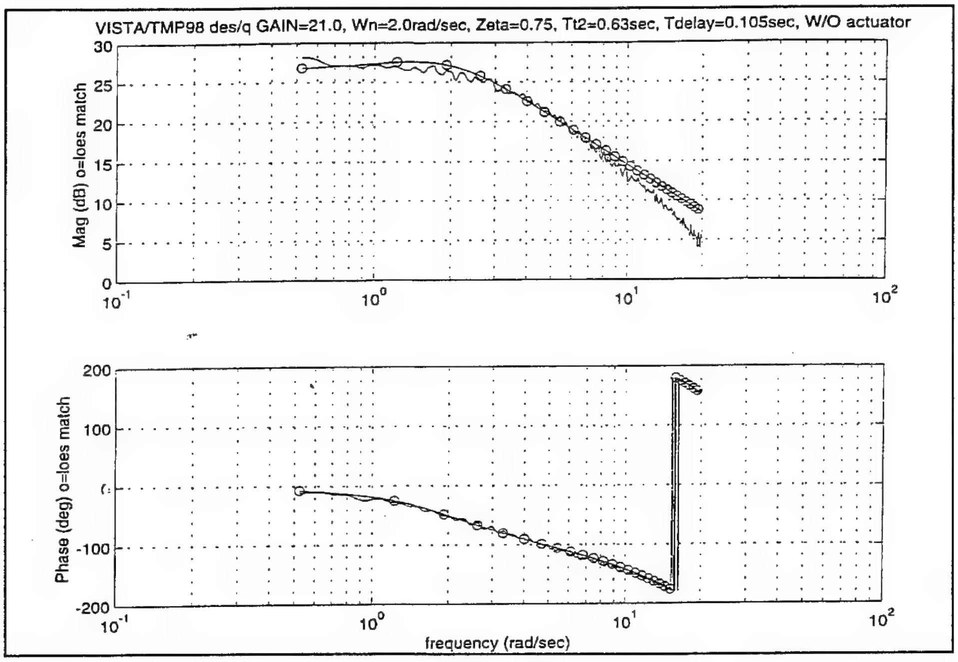


Figure B-4. Frequency Matching of Lower Order Equivalent System and Flight Data (Level 3 Aircraft)

Appendix C: Flight Test Log, Rating Scales, and Pilot Comments and Ratings

Table C-1. Flight Log

PROGRAM FLIGHT SUMMARY				
FLIGHT NUMBER	DATE / DURATION	EP/SP	TAPE #	RECORD COUNT
421	1 SEP 98/1.1	BALL/PEER	N/A	N/A
422	4 SEP 98/1.0	PEER/BALL	N/A	N/A
423	10 SEP 98/1.1	FORD/PEER	52	25
424	11 SEP 98/1.1	CHAPA/PEER	53	19
425	12 SEP 98/1.1	CHAPA/PEER	55	30
426	12 SEP 98/1.1	CHAPA/PEER	57	35
427	13 SEP 98/1.1	LETOURNEAU/PEER	59	32
428	13 SEP 98/1.1	PARKER/PEER	60	31
429	14 SEP 98/1.1	PARKER/PEER	61 63	27 28-33
430	14 SEP 98/1.1	LETOURNEAU/PEER	62	33
431	17 SEP 98/1.2	CHAPA/PEER	64	39
432	17 SEP 98/1.4	LETOURNEAU/PEER	65	44
433	18 SEP 98/1.4	PARKER/PEER	67	44

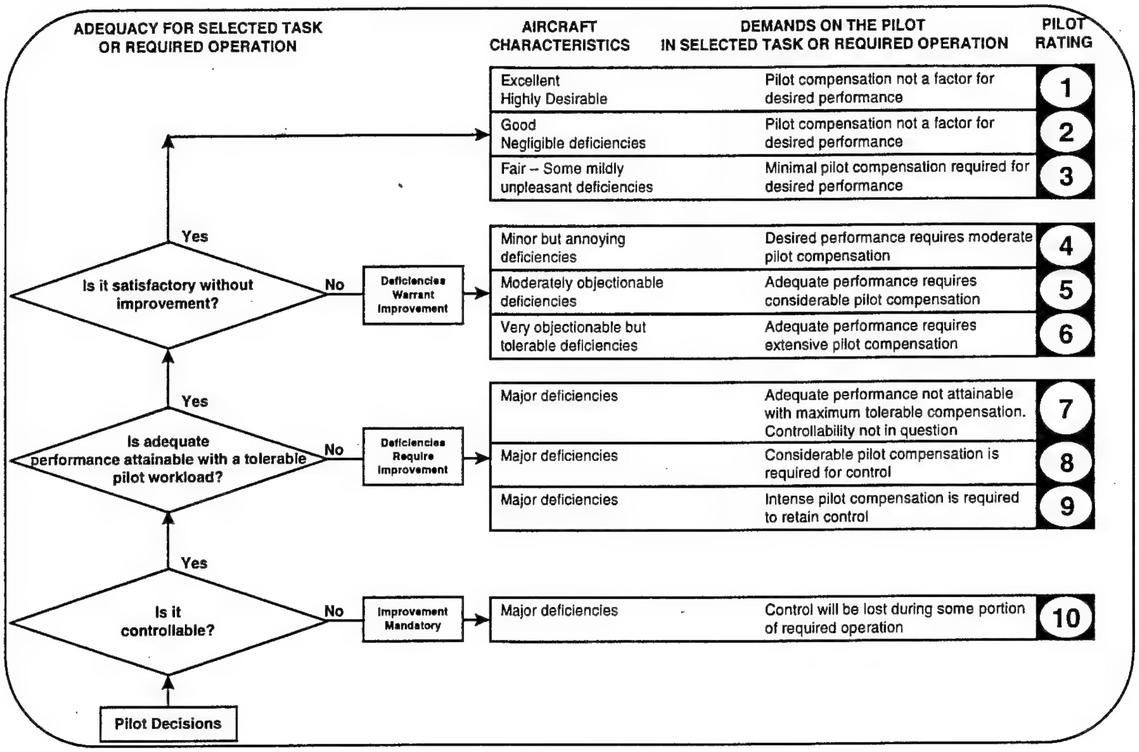


Figure C-1. Cooper-Harper Rating (CHR) Scale

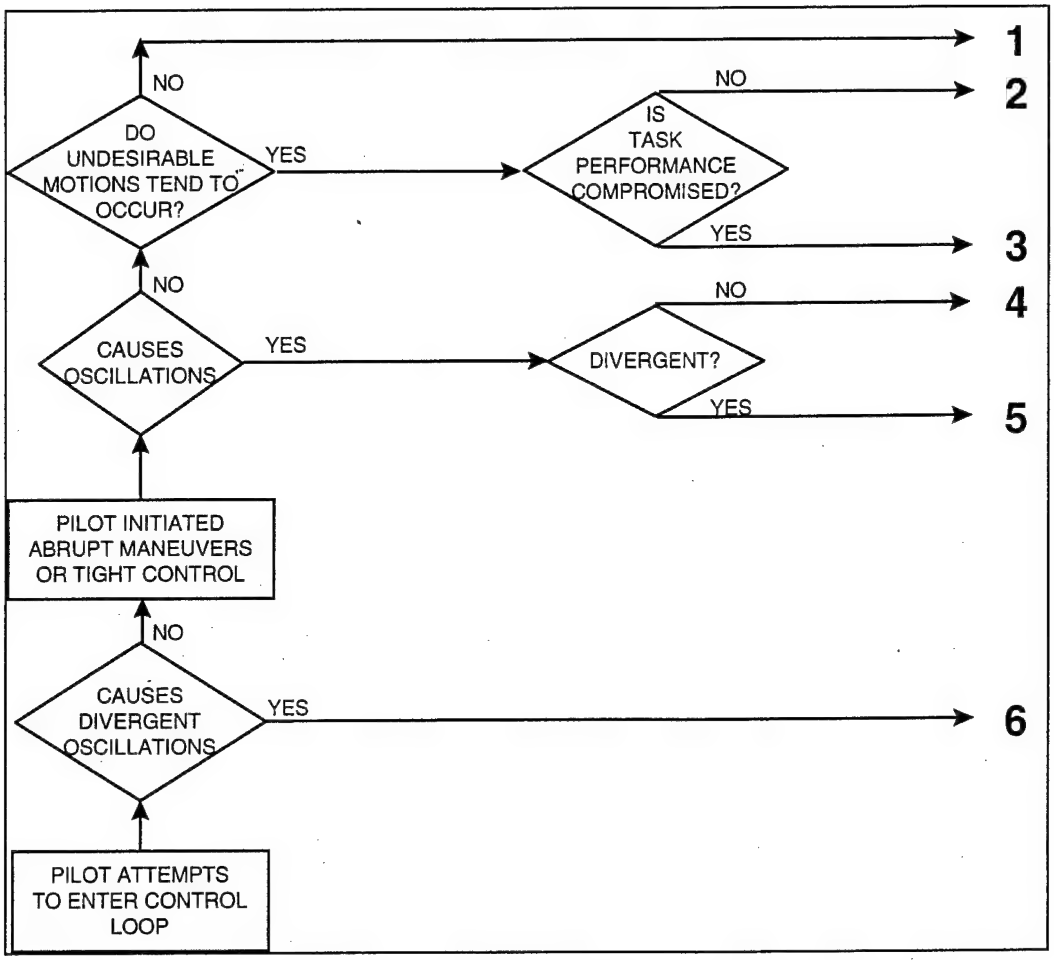


Figure C-2. Pilot-Induced Oscillation (PIO) Tendency Rating Scale

Pilot Comments and Ratings

LEGEND

Test Point: XXX - refers to the numbers in the test matrix found in Table 6-3.

Pilot/Flight Number (see Table C-1)
Phase Number: Pilot-Induced Oscillation Tendency Rating (PIOR), Departure Status, Pilot Comments
Phase Number: PIOR, Cooper-Harper Rating (CHR), Departure Status, Pilot Comments

Test Point: 100

Chapa/425
Ph II: 6 **DEPARTURE** - "Divergent departure?"
Ph III: 5 / 10 **DEPARTURE** - "Twitchy, coupling with it – big pull → Trip"

Chapa/431
Ph I: "Good initial response – then hangup → osc → dep"
Ph II: 5 **DEPARTURE** - "Very responsive initially"
Ph III: 5 / 10 **DEPARTURE** - "A little twitchy initial response w/ bobble, but it goes where I want it → easy to couple/osc. I like initial response trip → dep on big pull"

Letourneau/427
Ph I: "Much more sensitive response in pitch than [281]. Pitch bobbles during pitch captures."
Ph II: 4 **NO DEPARTURE** - "Had a sensation that it almost departed in negative n_z right at the end of the task. However, remained bounded."
Ph III: 3 / 5 **NO DEPARTURE** - "Fine tracking sensitivity made for undesirable motions that compromised task performance. Fine tracking more difficult due to initial pitch response sensitivity. Magnitude of undesirable motions during fine tracking caused adequate criteria to be met."

Letourneau/432
Ph I: "Lot more touchy – quick pitch rate buildup – difficult to arrest."
Ph II: 5 **DEPARTURE** - "Quickly growing oscillation."
Ph III: 5 / 10 **DEPARTURE** - "Very difficult to arrest oscillations on gross acquisition – eventually departed. Can feel it wanting to go – lots of pilot compensation."

Parker/428
Ph II: **5 - DEPARTURE**
Ph III: 4 / 4 **NO DEPARTURE** - "[Slowly decaying oscillations] wasted valuable tracking time – Difficult to track precisely. Oscillations were damped with effort which distracted from the task – i.e. workload increased"

Parker/433
Ph II: **6 - DEPARTURE**
Ph III: 4 / 4 **NO DEPARTURE** - "Damped on fine track, but it seemed on one occasion to be about to depart – huge q_dot excursion, saved by going out of loop. Suspect this as being on a tight rope, could go any time."

Test Point: 120

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5 / 10 **DEPARTURE** - "Nice initial response, but bobble/coupling"

Letourneau/430

Ph I: "Responsive but hard to pitch capture."

Ph II: 5 **DEPARTURE** - "Growing oscillations – felt responsive and in phase right up to departure – good departure – lots of roll coupling in task."

Ph III: 3 / 4 **NO DEPARTURE** - "Quite a bit of undesired motions due to sense of neutral stability. Definite task degradation. Good fine tracking – good initial pitch response – causes gross overshoots – very light stick forces for initial pitch motions – felt almost neutral stable in pitch."

Parker/429

Ph II: 5 **DEPARTURE**

Ph III: 3 / 4 **NO DEPARTURE** - "Fairly precise (quick), a little loose (bobbly). Not too bad."

Test Point: 121

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 6 / 10 **DEPARTURE** - "Very response, but easily induced oscillations"

Letourneau/427

Ph I: "Pitch sensitivity, 1 o/s on pitch captures"

Ph II: 3 **NO DEPARTURE** - "Bounded motion – initial pitch rate response a little fast."

Ph III: 3 / 5 **NO DEPARTURE** - "Sensitive in pitch – The fine tracking motions compromise task performance – need to back out slightly to damp out. Pitch bobble during fine tracking – overshoots on gross acquisition – too much pitch bobble to meet desired criteria – working hard to keep adequate criteria."

Parker/428

Ph II: 4 **NO DEPARTURE** - "Large amplitude corrections invoked greater rates of overshoots"

Ph III: **INCONCLUSIVE** "Never managed to stabilize the pipper on tgt for more than a second. Generally bounded PIO (small amplitude) – moderate compensation"

Test Point: 140

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5 / 10 **DEPARTURE** - "A little bobble, but good initial response – good initial response, but bobbles/PIO having to back out, PIO → Dep on big pull"

Letourneau/430

Ph I: "Very good initial pitch response – better pitch capture ability than [151].

Ph II: 5 **DEPARTURE** - "Not even bang-bang at departure – felt divergent and valid departure."

Ph III: 3 / 4 **NO DEPARTURE** - "Some pitch bobble right after gross acquisition. Very sensitive in pitch, but fine tracking not that difficult. Not rock steady in fine track, but workable."

Parker/429

Ph II: 5 **DEPARTURE**

Ph III: 4 / 5 **NO DEPARTURE** - "Erratic, oversensitive, difficult to be smooth."

Test Point: 141

Chapa/426

Ph II: 4 **NO DEPARTURE** - "Not responding to my input at times, don't like the response"

Ph III: 4 / 5 **NO DEPARTURE** - "Bobble, but response not too terrible – good initial response, a little oscillation – lots of little bobbles – performance deemed desired, but objectionable HQ deficiencies (bobbles)."

Chapa/431

Ph II: 5 **DEPARTURE** - "Twitchy"

Ph III: 4 / 5 **NO DEPARTURE** - "Pretty good initial response, then it hangs up – a little coupling at top (of big pulls), a little sluggish on bit pull → osc, able to stop it"

Letourneau/430

Ph I: "Very pitch sensitive – hard to arrest – lots of bobble."

Ph II: 4 **DEPARTURE** - "Very responsive, felt like a good departure – could feel the saturation."

Ph III: 4 / 6 **NO DEPARTURE** - "Little bobble – oscillations after gross acquisition – need to back out. Lots of overshoots on gross acquisition. Small improvement over [161]. Out of phase on gross acquisition."

Letourneau/432

Ph I: "Fast pitch rate buildup – twitchy."

Ph II: 3 **NO DEPARTURE** - "Bang-bang achieved. Degrading motions. Can feel changing pitch rates – initially responds to commands up to a point and then resists."

Ph III: 3 / 5 **NO DEPARTURE** - "Stepped buildup - causes degrading motions and unpredictability. Too much bobble while chasing the target. Stepped pitch rate buildup. Little twitchy."

Parker/429

Ph II: 5 **NO DEPARTURE**

Ph III: 4 / 6 **NO DEPARTURE** - "Too sensitive with obvious rate limiting. Not pleasant (but slightly better than [161]."

Parker/433

Ph II: 5 **DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE** - "A little loose – responsive but well damped during fine tracking. Nice."

Test Point: 150

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5 / 10 **DEPARTURE** - "Liked general response to small inputs – bobble, coupling"

Letourneau/430

Ph I: "Good initial pitch response."

Ph II: 4 **DEPARTURE**

Ph III: 4 / 6 **NO DEPARTURE** - "Pitch bobble during fine tracking. Backing out of loop to stop oscillations. Fine tracking difficult – out of phase on fine tracking. Overshoots on gross acq. – easy to over-control."

Parker/429

Ph II: **INCONCLUSIVE** - "Pitch rate slightly variable"

Ph III: 4 / 5 **NO DEPARTURE** - "The overall feel was loose system. Difficult to predict. Pipper placement was difficult to hold steady"

Test Point: 151

Chapa/426

Ph II: 4 **NO DEPARTURE** - "Strange response, and at times no control, i.e. the input was in with no aircraft response, but no departure

Ph III: **INCONCLUSIVE** - "A little bobble, very hard to control airplane – mind of its own, sucks"

Chapa/431

Ph II: 3 **NO DEPARTURE** - "A little non-responsiveness at times, but not divergent"

Ph III: 4 / 4 **NO DEPARTURE** - "Nice initial response, not too much bobbling, a little bobble after capture, coupling/PIO after big pull, had to back out – overall good, but a few minor exceptions"

Letourneau/430

Ph I: "Very responsive in pitch – difficult to fine track."

Ph II: **INCONCLUSIVE** - "Felt like a good departure – growing oscillation – felt like controls saturated."

Ph III: 3 / 5 **NO DEPARTURE** - "Pitch bobble degraded task performance. Bad pitch bobble. More squirrely trying to settle on fine tracking (than [251]). Could not maintain desired criteria due to bobble."

Letourneau/432

Ph I: "Slower pitch rate buildup than [160] – still sensitive – difficult to arrest pitch rate smoothly."

Ph II: 4 **NO DEPARTURE** - "Can feel changing pitch rate responses during portions of HQDT. Prevents departures as aircraft initially ignores pilot commands – appeared as a large delay – would cycle in and out of the pitch response delay."

Ph III: 4 / 8 **NO DEPARTURE** - "Twitchiness around fine tracking. Controllability in question – especially when aircraft reacting opposite to inputs. Intermittent delays in aircraft response. Made it very unpredictable – sense that system was helping to prevent a departure. Mixed with roll task seems to unmask same controllability issues not present in Phase II."

Parker/429

Ph II: 4 **NO DEPARTURE**

Ph III: 4 / 5 **NO DEPARTURE -** "Very springy/oscillatory. Lots of overshoots – too loose. Hard work getting adequate."

Parker/433

Ph II: 6 **DEPARTURE**

Ph III: 4 / 4 **NO DEPARTURE -** "Gross acquisition, 2 to 3 overshoots every time. Fairly well damped, enabling fine tracking. Needs improvement."

Test Point: 160

Chapa/426

Ph II: 4 **NO DEPARTURE -** "Carnival ride, loose but not divergent"

Ph III: **INCONCLUSIVE -** "Bobbling a little"

Chapa/431

Ph II: 4 **NO DEPARTURE**

Ph III: 4 / 6 **NO DEPARTURE -** "Crisp initial response, but easy to couple, bobbling/coupling – not real desirable, coupling – had to back out, difficult to capture large pull → osc"

Letourneau/430

Ph I: "Good onset of pitch rate – bobble on tight control."

Ph II: **INCONCLUSIVE -** "Bang-bang achieved – felt like a good departure."

Ph III: 5 / 10 **DEPARTURE -** "PIO after gross acquisition – need to back out. Bobble on fine tracking. Exponentially worse with more aggressive maneuvering."

Letourneau/432

Ph I: "Much more responsive, very sensitive – fast pitch rate buildup difficult to arrest."

Ph II: **INCONCLUSIVE -** "Stop-stop achieved – very responsive – bounded oscillation."

Ph III: 5 / 10 **DEPARTURE -** "Very twitchy. Very sensitive pitch response. Pitch rate buildup got out of control."

Parker/429

Ph II: 3 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE -** "Precise, small pitch bobbles but desired met. Fine tracking easy, gross acq not so good , but desired. 2 or 3 overshoots."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4 / 6 **NO DEPARTURE -** "Almost impossible to damp whilst in the loop. Hard work."

Test Point: 161

Chapa/426

Ph II: **INCONCLUSIVE**

Ph III: 4 / 6 **NO DEPARTURE -** "Sometimes the aircraft response doesn't match inputs. Nice initial response, but some bobble/coupling – lots of bobble → PIO, uncommanded response, sluggish, doing its own thing at times, large input → not much response."

Chapa/431

Ph I: "Good initial response – able to stop it – I like it"

Ph II: 3 **NO DEPARTURE -** "Some uncommanded motion (no response)"

Ph III: 4 / 5 **NO DEPARTURE -** "A little bobble after good initial response – fair amount of bobbling, slow on <u>big pull</u> and then undesirable – lack of response, lots of bobble"

Letourneau/430

Ph I: "Fast pitch ramp-up difficult to arrest."

Ph II: **INCONCLUSIVE -** "Bang-bang achieved – felt like it was hanging in there but good departure."

Ph III: 4 / 8 **NO DEPARTURE -** "Bounded oscillations throughout – required backing out. Not easy to control. Lots of pitch rate inertia. Horrible configuration. Feels like changing flight control gains."

Letourneau/432

Ph I: "Little touchy."

Ph II: 4 **NO DEPARTURE -** "Initially good pitch rate buildup – stop to stop. Can occasionally feel pitch response delays – sense of keeping oscillations bounded."

Ph III: 4 / 8 **NO DEPARTURE -** "Touchy in fine tracking – sense that variable pitch rates were keeping oscillations bounded. Good initial response – tough to arrest. Controllability in question as pitch rate response changes throughout maneuver – however – while it seems the aircraft is fighting my inputs on occasion there is a sense that it is helping to prevent a departure by arresting a pitch rate prior to honoring a command."

Parker/429

Ph II: **INCONCLUSIVE -** "Very loose/unpredictable. Rate limiting. Over sensitive"

Ph III: 4 / 6 **NO DEPARTURE -** "You could feel rate limiting on this one. Pitch rate was not linear to input. Made it difficult to be accurate. Hard work."

Parker/433

Ph II: 4 **NO DEPARTURE -** "Lots of rate limiting. Questionable control."

Ph III: 4 / 5 **NO DEPARTURE -** "Predictability was the biggest issue. Although it did not depart, it lacked the precision needed to attain desired results."

Test Point: 180

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 3 / 4 **NO DEPARTURE -** "A little bobble, overshoot, PIO (multiple) – hard to back out some"

Letourneau/427

Ph I: "Feels like a lead filter. Pitch rate buildup is faster at input then at steady-state."

Ph II: 4 **NO DEPARTURE** - "Extreme initial sensitivity caused a small bounded oscillation."

Ph III: 3 / 4 **NO DEPARTURE** - "Gross acquisition overshoots. Initial input sensitivity compromised task performance. Initial sensitivity required backing off aggressiveness to meet desired performance (on tape review it appeared to be adequate performance)."

Letourneau/432

Ph I: "Touch pitch response – bobbly – hard to arrest."

Ph II: 4 **NO DEPARTURE** - "Stop-to-stop. Bounded oscillation."

Ph III: 4 / 8 **NO DEPARTURE** - "Feel motions grow in amplitude and have to back out to keep things bounded -- never quite dampens out. Sensitive in initial acquisition. Controllability in question. Had to back out on several occasions. Roll task seems to unmask problems not inherent in Phase II."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 3 / 3 **NO DEPARTURE** - "Small annoying pitch bobbles – present with aggressive tracking – Gross acquisition was difficult to achieve without at least one or two overshoots. Fine acquisition was better but not as precise as I would have liked (Desired)"

Parker/433

Ph II: 3 **NO DEPARTURE**

Ph III: 4 / 4 **NO DEPARTURE** - "Too sensitive and "springy" for fine track, otherwise OK."

Test Point: 181

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE** - "Pitch rate buildup (non-linear response), sluggish, bobbles – do not like response, can't do anything with it – sucks"

Chapa/431

Ph II: 4 **NO DEPARTURE** - "Something uncommanded going on there"

Ph III: 4 / 8 **NO DEPARTURE** - "Crisp initial response, the buildup to hangup of uncommanded nature – big overshoot, uncommanded no response – had to back out of loop then osc, initial pull good, but shortly thereafter not always responsive – very undesirable"

Letourneau/427

Ph I: "Very sensitive in pitch. Lots of bobble – difficult to pitch capture."

Ph II: **INCONCLUSIVE** - "Growing oscillation with bang-bang technique. Large delay in pitch onset rate and then fast ramp up."

Ph III: 4 / 7 **NO DEPARTURE** - "Delay in pitch rate onset and then steep ramp up caused large overshoots in gross acquisition. Extreme pilot compensation minimized the magnitude of the overshoot. Bounded oscillation during fine tracking. Felt it was due to the delay and then steep ramp up of pitch rate. Controllability not in question, but extreme pilot compensation was unable to meet adequate criteria."

Letourneau/432

Ph I: "Quick pitch rate buildup – hard to arrest – some bobble."

Ph II: 3 **NO DEPARTURE -** "Can feel changing pitch rate responses – almost a 1.5 second delay at times before responding to commands and nearly instantaneous at others – seemed to prevent a bounded oscillation."

Ph III: 4 / 8 **NO DEPARTURE -** "Sense of bounded oscillation during most acquisitions requiring backing out of system. Good initial acquisition. Fighting my inputs – easily saturated. <u>Extreme</u> pilot compensation, trying to guess when pitch rates would change. Roll task helped unmask some controllability issues. Felt like it almost departed towards the end of the task, but compensation prevented it."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4 / 8 **NO DEPARTURE -** "Pitch control extremely erratic, Q was oscillatory – major problem during tracking. Predictability was very poor. Overshoots were large amplitude. Not good."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3 / 6 **NO DEPARTURE -** "Too unpredictable. Q_dot varied too much. Obvious rate limiting. When not in rate limit, system was too loose."

Test Point: 200

Chapa/425

Ph II: **INCONCLUSIVE -** "Hanging together"

Ph III: 2 / 3 **NO DEPARTURE -** "Little overshoots, but able to stop it – I like the response, handling very well, little coupling, nice response on big pull – Liked it, but sometimes an overshoot that was stoppable"

Chapa/431

Ph II: 4 **NO DEPARTURE -** "Very big overshoots in up direction"

Ph III: 3 / 5 **NO DEPARTURE -** "Sluggish initial response – pitch rate buildup – overshoots – dampens OK after pull, a little PIO trying to stop pitch rate, overshoot able to stop"

Letourneau/427

Ph I: "Small delay on pitch input, but ramps up nicely. Well behaved."

Ph II: 3 **NO DEPARTURE -** "Some undesirable motions but aircraft responding well. Faster pitch rate buildup than [221] causes larger overshoots. Bang-bang achieved wth no bounded oscillations."

Ph III: 2 / 3 **NO DEPARTURE -** "Only small undesired motions during fine tracking. 2 overshoots on gross acquisition. Fine tracking much easier in this configuration. Well behaved and predictable."

Letourneau/432

Ph I: "Little more responsive than [261] – still feels well behaved.

Ph II: 3 **NO DEPARTURE -** "Stop-to-stop. Aircraft responds very nicely."

Ph III: 2 / 3 **NO DEPARTURE -** "Solid in fine tracking. Gross acquisition simple. Just about right. Liked it best."

Parker/428

Ph II: 4 **NO DEPARTURE**

Ph III: 2 / 3 **NO DEPARTURE** - "Better. Damped somewhat, but not perfect"

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE** -"Too sluggish, but helped with the desired score. Any larger K_task would probably degrade the HQ of this system. Slightly bobbly when in tight loop."

Test Point: 220

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 2 / 3 **NO DEPARTURE** -"Fairly sluggish, no residual coupling after gross acq, bobble (a little) – big acq liked response"

Letourneau/427

Ph I: "Very similar to [250]. Little less response in pitch."

Ph II: 3 **NO DEPARTURE** -"Little slow to respond – stick motion – stop to stop – aircraft motion was not quick, but not a degrading lag. Not a bounded oscillation."

Ph III: 3 / 5 **NO DEPARTURE** -"Sluggishness made for undesirable motions, but no PIO tendency. Objectionably sluggish response. Made getting to a fine tracking solution difficult. Once there it was a stable platform."

Parker/428

Ph II: 5 **NO DEPARTURE** -"Divergent. Task finished before departure – probably would have departed if the task was longer."

Ph III: 4 / 4 **NO DEPARTURE** -"Oscillations occurred throughout which were more prevalent with aggressive/large amplitude inputs"

Test Point: 221

Chapa/425

Ph II: 3 **NO DEPARTURE** -"Some growth in bounded osc, but arrested back into non-divergent tracking"

Ph III: 2 / 4 **NO DEPARTURE** -"Pitch rate buildup, a little sluggish but stopped on a dime, a little unpredictable, but able to stop it nicely on big pull"

Letourneau/427

Ph I: "Pretty nice airplane, very responsive."

Ph II: **INCONCLUSIVE** - "Reached bang bang early on. Aircraft extremely responsive, no tendency to PIO."

Ph III: 2 / 3 **NO DEPARTURE** -"Small overshoots on gross acquisition but did not compromise task performance. Very well behaved, best configuration so far during the flight. Nice initial response and steady state response on gross acquisition."

Parker/428

Ph II: 3 **NO DEPARTURE**

Ph III: 2 / 3 **NO DEPARTURE** - "Minor bobbles. Controllable, but not acceptable. Max aggression still achieved desired – video suggested only adequate [rated as desired]"

Test Point: 240

Chapa/426

Ph II: 3 **NO DEPARTURE** -"Seems to be hanging pretty good – not much undesirable"

Ph III: **INCONCLUSIVE** -"A little sluggish initial response, a little bobble – I like the response for the most part"

Chapa/431

Ph II: **INCONCLUSIVE**

Ph III: 4 / 5 **NO DEPARTURE** -"A little sluggish initial response, some small osc in fine tracking, some coupling"

Letourneau/430

Ph I: "Slower pitch rate ramp-up."

Ph II: **INCONCLUSIVE** - "Bang-bang achieved. Not as responsive in negative pitch rate."

Ph III: 3 / 4 **NO DEPARTURE** -"Minor bobble on fine tracking. Solid fine tracking. Pretty stable. Slower initial response."

Letourneau/432

Ph I: "Sluggish, slow pitch buildup."

Ph II: 3 **INCONCLUSIVE** - "Bang-bang achieved – behaved well."

Ph III: 3 / 5 **NO DEPARTURE** -"Little twitchy in fine tracking. Little sluggish – slow ramp up in pitch rate. Sluggish response made meeting desired criteria not possible."

Parker/429

Ph II: 4 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE** -"Nice. Fine tracking a bit bobbly – Gross acq – nice, damped, easy to predict."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4 / 5 **NO DEPARTURE** - "Difficult to accurately predict gross acquisition. Fine tracking purity was spoiled by bobbles (lots of them)."

Test Point: 241

Chapa/426

Ph II: 3 **NO DEPARTURE** -"Wasn't quite as responsive as I would have liked."

Ph III: 3 / 4 **NO DEPARTURE** -"Fairly sluggish on initial pull w/ pitch rate buildup – a little PIO, bug overshoots w/ some residual oscillations, much of the tracking was fine"

Chapa/431

Ph II: **INCONCLUSIVE** - "Sluggish initial response to large overshoots"

Ph III: 3 / 6 **NO DEPARTURE** -"Big overshoots on pitch capture w/ pitch rate buildup – Ph I. Sluggish initial response, can't stop airplane where I want it."

Letourneau/430

Ph I: "Slower pitch rate buildup – more solid feel."

Ph II: **INCONCLUSIVE**

Ph III: 2 / 3 **NO DEPARTURE** -"Minimal bobble. Initial pitch response a touch sluggish – helps to minimize overshoots. Minimal bobble – tracks real nice. Felt like a heavier stick."

Letourneau/432

Ph I: "Slower but steady pitch buildup. More deadbeat."

Ph II: 3 **NO DEPARTURE** -"Well behaved. Stop to stop."

Ph III: 3 / 4 **NO DEPARTURE** -"Undesirable motions during fine track while the target was moving degraded performance. Nice in gross acquisition."

Parker/429

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE** - "Departure – quite likely. Very difficult to track with any precision."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4 / 6 **NO DEPARTURE** -"Very sluggish. Difficult to maintain zero error for more than 1/4 second due to bobbles."

Test Point: 250

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 3 / 4 **NO DEPARTURE** -"Very sluggish, big delay – No residual bobble after gross acq, but not real responsive, a little unpredictable"

Letourneau/427

Ph I: "Small lag in pitch response, but steady pitch rate."

Ph II: 3 **NO DEPARTURE** -"Very well behaved, aircraft responded very quickly to inputs. Stich motion achieved stop-to-stop by middle of task with no degrading lag."

Ph III: 3 / 4 **NO DEPARTURE** -"Much better damped than [180]. Pipper moves much less during fine tracking. Overshoots on gross acquisition. Predictable aircraft."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4 / 5 **NO DEPARTURE** - "Adequate, high workload"

Test Point: 251

Chapa/426

Ph II: 3 **NO DEPARTURE** -"Sluggish response, but hung together"

Ph III: **INCONCLUSIVE** - "Pitch rate buildup, sluggish initial response, good damping on large inputs, hard to make the thing do what I want in pitch at times"

Chapa/431

Ph I: "Big, huge overshoot, sluggish response"

Ph II: 4 **NO DEPARTURE** - "Sluggish, big overshoots, slow turn around"

Ph III: 3 / 5 **NO DEPARTURE** - Sluggish initial response, damps well, very sluggish, a little bobble after big overshoot on big pull – able to stop it"

Letourneau/430

Ph I: "Slower pitch rate buildup – hard to arrest once going."

Ph II: **INCONCLUSIVE -** "Bang-bang during HQDT. Oscillations growing – left with impression of impending departure."

Ph III: 2 / 3 **NO DEPARTURE -** "Solid in fine track. Initial acquisition good. Little bit of roll coupling from turbulence."

Letourneau/432

Ph I: "Slower pitch rate buildup – easy to arrest."

Ph II: 3 **NO DEPARTURE -**"Pitch rate buildup feel [parabolic/quadratic] – good response throughout – stop-to-stop."

Ph III: 2 / 3 **NO DEPARTURE -**"Steady tracking – deadbeat during fine tracking. Well behaved – very nice. Easily arrested pitch rate – deadbeat. Predictable behavior."

Parker/429

Ph II: **INCONCLUSIVE**

Ph III: 3 / 4 **NO DEPARTURE -**"Sluggish pitch with low predictability"

Parker/433

Ph II: 3 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE -**"Well damped. Predictable and nice (relatively speaking)."

Test Point: 260

Chapa/431

Ph II: 4 **NO DEPARTURE -**"Sluggish, slow to turn around, big overshoots"

Ph III: 3 / 5 **NO DEPARTURE -**"Bit overshoots – not real crisp – pitch rate buildup, then hang up (Ph I) – sluggish initial response, but stops OK. Nice stop on big pull but sluggish initial response."

Letourneau/432

Ph I: "Nice plane. Decent pitch response & buildup. Maybe a touch sensitive in fine tracking."

Ph II: 3 **NO DEPARTURE -**"Stop to stop – well behaved."

Ph III: 2 / 3 **NO DEPARTURE -**"Well behaved. Tracks well – fine tracking."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE -**"A little sluggish but helpfully so. Fairly well damped. Nice."

Test Point: 261

Chapa/426

Ph II: **INCONCLUSIVE -** "A little sluggish to inputs"

Ph III: **INCONCLUSIVE -** "Pitch rate buildup, unpredictable – a little sluggish on big pulls"

Chapa/431

Ph II: 4 **NO DEPARTURE** -"Very large overshoots, sluggish reversals at top, similar to [281]"

Ph III: 4 / 5 **NO DEPARTURE** -"Big overshoots, sluggish initially, pitch rate buildup – sluggish initial response → overshoot tendency – osc @ top of big pull, overshoot"

Letourneau/430

Ph I: "Feels nice."

Ph II: **INCONCLUSIVE**

Ph III: 2 / 3 **NO DEPARTURE** - "Good initial acquisition. Solid fine tracking. Touch sluggish in pitch response. Pitch rate buildup but not very predictable on small gross acq."

Letourneau/432

Ph I: "Maybe a little slower pitch rate buildup than [281] – but solid."

Ph II: 3 **NO DEPARTURE** - "Stop to stop – behaving really well – responding as soon as inputs are put in."

Ph III: 2 / 3 **NO DEPARTURE** - "Like a rock for fine tracking. Easy gross acquisition."

Parker/429

Ph II: 3 **NO DEPARTURE**

Ph III: 4 / 4 **NO DEPARTURE** - "Sluggish with varying q_dot – makes it slightly difficult to predict and track. Worked hard to get a 4."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3 / 3 **NO DEPARTURE** - "Relatively sluggish and damped allowing for desired performance. Nice."

Test Point: 280

Chapa/425

Ph II: 3 **NO DEPARTURE** - "A little sluggish, especially on large reversal"

Ph III: 3 / 4 **NO DEPARTURE** - "Pretty good, a little sluggish, a little PIO on big pull – able to arrest it"

Letourneau/427

Ph II: 4 **NO DEPARTURE** - "Definite bounded oscillation. May have been growing slowly. General sense that it was going to depart but the task ended. Bang-bang achieved."

Ph III: 3 / 4 **NO DEPARTURE** - "Bobble on gross acquisition. Very subtle motion during fine tracking – aircraft seems to bobble without stick inputs. Fine tracking motions make desired performance difficult but achievable."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4 / 5 **NO DEPARTURE** - "Gross acq – many overshoots – very objectionable bobbles, very hard work to get adequate"

Test Point: 281

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE**

Chapa/431

Ph II: 4 **NO DEPARTURE -** "Big overshoots, very sluggish"

Ph III: 4 / 6 **NO DEPARTURE -** "Sluggish initial response – pitch rate buildup – overshoots – harmony poor (roll more responsive) – oscillations on big pull @ top – can't stop aircraft once you get it going"

Letourneau/427

Ph I: "Not as responsive in pitch as [121], lag in the response – motion continues after controls neutralized, more evidence of lag as the motion does not damp out."

Ph II: 4 **NO DEPARTURE -** "Definite bounded oscillations – appears to be due to pitch response lag."

Ph III: 3 / 4 **NO DEPARTURE -** "Pilot compensation under tight control created an undesirable motion, but the level of compensation required compromised task performance. More sluggish response than [121] makes for better gross acquisition. 2 o/s on gross acquisition. More stable pipper during fine tracking than in [121]."

Letourneau/432

Ph I: "Slower pitch rate buildup than [141] – deadbeat – likable."

Ph II: 3 **NO DEPARTURE -** "Steady pitch rate buildup – stop-stop. Pretty good airplane."

Ph III: 2 / 3 **NO DEPARTURE -** "Solid fine tracking – no objectionable bobble. Maybe a little sluggish overall but good initial response. Able to arrest pitch rates easily on gross acquisition."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4 / 5 **NO DEPARTURE -** "Bounded, annoying oscillations – Slacked out of the loop a bit to reduce the amplitude of overshoots – adequate performance but high workload"

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 3 / 4 **NO DEPARTURE -** "Initial response – too sensitive but damped enough to achieve desired. Generally a tight system on fine tracking."

Bibliography

A'Harrah, Ralph C. "An Alternate Control Scheme for Alleviating Aircraft-Pilot Coupling," Proceedings of the AIAA Guidance and Control Conference. Scottsdale AZ, 1-3 August 1994.

Anderson, Mark R. and Anthony B. Page, "Multivariable Analysis of Pilot-in-the-Loop Oscillations," AIAA-95-3203-CP, Proceedings of the AIAA Atmospheric Flight Mechanics Conference. 278-287. Scottsdale AZ, 1-3 August 1994.

Anderson, Mark R. and Anthony B. Page. Unified Pilot-Induced Oscillation Theory, Volume III: PIO Analysis Using Multivariable Methods, Final Report. Contract No. F33615-94-C-3611. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Ashkenas, I.L., H.R. Jex, and D.T. McRuer. Pilot-Induced Oscillations: Their Cause and Analysis. NORAIR Report No. NOR-64-143, Northrop Corporation, June 1964 (AD-481 994).

Berthe, C. Background and Narrative for PIO Film Clip, Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, August 1984.

Buckley, J., K. Citrus, J. Hodgkinson, R. Hoh, D. Mitchell, and J. Preston. Unified Pilot-Induced Oscillation Theory, Volume II: Pilot-Induced Oscillation Criteria Applied to Several McDonnell Douglas Aircraft, Final Report. Contract No. F33615-94-C-3612. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Chapa, M., Fick, E., Kraabel, D., LeTourneau, M, and Parker, T., Results of Attempts to Prevent Departure and/or Pilot-Induced Oscillations (PIO) Due to Actuator Rate Limiting in Highly Augmented Fighter Flight Control Systems, Final Report, AFFTC-TR-98-26, Edwards AFB CA, December 1998.

Crassidis, A. L. NT-33A Air Force Test Pilot School Spring '97 Test Management Projects Analysis and Results. Document No. TM-056-NT33A-0674-R00, Calspan SRL Corporation, Buffalo NY, 9 September 1997.

Department of Defense. Military Standard, Flying Qualities of Piloted Aircraft. MIL-STD 1797A, 30 January 1990.

Deppe, P.R., Chalk, C.R., and M. Shafer. Flight Evaluation of an Aircraft With Side and Centerstick Controllers and Rate-Limited Ailerons. Final Report No. 8091-2, Advanced Technology Center, Calspan Corporation, Buffalo NY, April 1994.

Doman, D.B., and B.A. Kish. Interactive Flying Qualities Toolbox for MATLAB™ V1.0. USAF Wright Laboratory, Flight Dynamics Directorate, Flight Control Division, Flying Qualities Section, Wright-Patterson AFB OH, August 1995.

Duda, Holger, and Bernd Krag. "Prediction of PIO-Susceptibility of Highly Augmented Aircraft due to Rate Limiting Elements in Flight Control Systems," Presentation at "Full Envelope Agility" Workshop. Eglin AFB FL, 28-30 March 1995.

Durham, Wayne C. and Kenneth A. Bordignon. "Multiple Control Effector Rate Limiting," AIAA-95-3425-CP, Proceedings of the AIAA Guidance, Navigation and Control Conference. 318-327. Scottsdale AZ, 1-3 August 1994.

Bibliography (cont.)

"Flight 5365." HAVE LIMITS/HAVE GAS, Data Release II, CD-ROM, Flight Control Division, Wright Laboratory, Wright-Patterson AFB OH, 7 July 1997.

Hammet, Kelly D., Jordan M. Berg, Carla A. Schwartz, and Siva S. Banda. "Stability Considerations in Daisy Chaining," Proceedings of the AIAA Guidance, Navigation and Control Conference. Scottsdale AZ, 2-3 August 1994.

USAF Test Pilot School, Flying Qualities Course Objectives, Edwards AFB CA, 30 March 1998.

Hutchinson, K. T., Partial Flight Manual, NF-16D 86-0048, Calspan Document WI-056-NF16D-0071, Supplement 6, August 18, 1998.

Kish, B.A., W.B. Mosle III, A.S. Remaly, J.S. Seo , J.F. Kromberg, and R. Cabiati, "A Limited Flight Test Investigation of Pilot-Induced Oscillation Due to Rate Limiting," Proceedings of the AIAA Guidance,Navigation and Control Conference, AIAA-97-3703, 1332-1341, New Orleans LA, 11-13 August 1997.

Klyde, David H., Duane T. McRuer, and Thomas T. Myers. "PIO Analysis with Actuator Rate Limiting," Proceedings of the AIAA Atmospheric Flight Mechanics Conference. San Diego CA, 29-31 July 1996.

Klyde, David H., Duane T. McRuer, and Thomas T. Myers. Unified Pilot-Induced Oscillation Theory, Volume I: PIO Analysis With Linear and Nonlinear Effective Vehicle Characteristics, Including Rate Limiting, Final Report. Contract No. F33615-94-C-3613. Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB OH, December 1995.

Koper, Judith. An Approach for Compensating Actuator Rate Saturation. Interim Report No. NADC-87120-60. Air Vehicle and Crew Systems Technology Department, NAVAL AIR DEVELOPMENT CENTER, Warminster PA, August 1987.

Leggett, Dave. Flying Qualities Engineer, Air Vehicles Division, Air Force Research Laboratory, Wright-Patterson AFB OH. Personal Interview. 19-21 Oct 1997.

MATLAB™ & SIMULINK™. Versions 5.1 and 2.1. Computer Software. The Mathworks, Inc., Natick MA, 1997.

McRuer, Duane T. Pilot-Induced Oscillations and Human Dynamic Behavior. NASA CR-4683, NASA Dryden Research Center, Edwards AFB CA, July 1995.

McRuer, Duane T., David H. Klyde, and Thomas T. Myers. "Development of a Comprehensive PIO Theory," Proceedings of the AIAA Atmospheric Flight Mechanics Conference. San Diego CA, 29-31 July 1996.

Mitchell, David G. and Roger H. Hoh. Development of a Unified Method to Predict Tendencies for Pilot-Induced Oscillations. WL-TR-95-3049, Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson AFB, OH, June 1995.

Ohmit, E.E.. Aerospace Engineer, Calspan Corporation, Buffalo NY. Telephone Interview. 8 Oct 1997.

Bibliography (cont.)

Ohmit, E.E. NT-33A In-Flight Investigation into Flight Control System Rate Limiting. Final Report No. 7738-24, Advanced Technology Center, Calspan Corporation, Buffalo NY, February 1994.

Peters, Patrick J. The Effects of Rate Limiting and Stick Dynamics On Longitudinal Pilot-Induced Oscillations. MS Thesis, AFIT/GAE/ENY/97M-02. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1997.

Rundqwist, Lars. Rate Limiters With Phase Compensation. ICAS-96-3.11.1. Saab Military Aircraft, Linkoping, Sweden, 1996.

Rundqwist, L., and Hillgren, Robert. Phase Compensation of Rate Limiters in JAS 39 Gripen. AIAA-96-3368-CP. Saab Military Aircraft, Linkoping, Sweden.

Rundqwist, L., Stahl-Gunnarsson, K., and Enhagen,, J. Rate Limiters With Phase Compensation In JAS 39 Gripen. Saab Military Aircraft, Linkoping, Sweden.

Smith, Ralph H. "Observations on PIO," Flight Vehicle Integration Panel Workshop on Pilot-Induced Oscillations, AGARD-AR-335, February 1995.

Smith, Ralph H. "Predicting and Validating Fully-Developed PIO," Proceedings of the AIAA Guidance, Navigation and Control Conference. AIAA-94-3669, *1162-1166.* Scottsdale AZ, 2 August 1994.

Smith, Ralph H. A Theory for Longitudinal Short-Period Pilot Induced Oscillations. AFFDL-TR-77-57, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB OH, June 1977.

Stevens, B.L., and F.L. Lewis. Aircraft Control and Simulation. John Wiley & Sons, NY, 1992.

USAF Test Pilot School, Flying Qualities Course Objectives. Edwards AFB CA, 30 March 1998.

Vita

Captain Michael J. Chapa was born 2 June 1966 in Newport News, Virginia. He graduated from Summerville High School, Summerville, South Carolina in 1984. He went on to earn a Bachelor of Science degree in Astronautical Engineering with Academic Distinction from the United States Air Force Academy in 1989.

After graduation, he entered Undergraduate Pilot Training at Williams AFB, Arizona, where he received his wings in August 1990. Capt Chapa went on to serve as an F-15C instructor/evaluator pilot in the 67th Fighter Squadron at Kadena AB, Okinawa, Japan, from May 1991 to November 1994. In February 1995, Capt Chapa joined the 414th Combat Training Squadron, Adversary Tactics Division, at Nellis AFB, Nevada, serving as an F-16C aggressor instructor pilot. As an operational threat expert, Capt Chapa simulated the threat for the world's premier air combat exercise, RED FLAG.

He entered the joint Air Force Institute of Technology/USAF Test Pilot School program in May 1996. A distinguished graduate of class 98A from the USAF Test Pilot School, Capt Chapa was assigned to the 416th Combined Test Force at Edwards AFB, CA, flight testing modifications to the F-16.

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13. ABSTRACT *(Maximum 200 words)*

Closed loop instability caused by excess phase lag induced by actuator rate limiting has been suspected in many aircraft departures from controlled flight and pilot-induced oscillations (PIO). As part of the joint Air Force Institute of Technology/Test Pilot School (AFIT/TPS) program, a nonlinear rate limiter pre-filter (RLPF) was developed to minimize the phase lag induced by rate limiting.

RLPF performance was evaluated inside the feedback path, but primary emphasis was on the pilot command path. Closed loop computer and motion-based flight simulation were conducted to prepare for the flight test. The HAVE FILTER flight test project was flown using the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) aircraft and evaluated using a software rate limit (SWRL) with and without an RLPF on the pilot command path. A programmable heads-up-display (HUD) was used to generate a fighter tracking task.

Flight test results showed the SWRL was useful in preventing departure and/or PIO. However, with low SWRL settings (<40 deg/sec) handling qualities deficiencies were uncovered due to sluggish initial pitch response.

The RLPF plus SWRL combination resulted in more departure and/or PIO protection than the SWRL alone. But, with low SWRL settings (<40 deg/sec) significant handling qualities deficiencies were sometimes found.

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